Dr. Paver

President, Center of Injury Research, a nonprofit 501(3c)

Education:

- B.S., 1977, Engineering, Harvey Mudd College
- M.S., 1980 and PhD,1985, Biomedical Engineering, Duke University

Expertise:

- Physical testing of fresh cadaveric and ATD necks and lumbar spines at Duke University
- WPAFB...Summer Faculty fellowship and research grant recipient in 1987-1989 testing, modeling, and troubleshooting
- Membership in SAE Dummy Users Group since 1987 and recently in SAE Aircraft Seat Committee
- Proficient in ATB, Head-Spine Model and LS-DYNA simulations of automotive, aerospace and other injury-producing environments
- Conducted full-scale dynamic rollover crash testing with ATDs and developed a more biofidelic compliant ATD neck for physiological pre-failure loading
- 35 years of expert biomechanical engineering analysis of real-world injuries

Facilitating a Safe Ejection Environment for the Aircrew Population: Protecting against Known Spinal Injury Patterns and Mechanisms

This presentation aims to:

1. **provide insights into real-world patterns and mechanisms of spinal injuries during aircrew ejections,**
2. **explore protective device evaluation criteria, and**
3. **discuss physical and virtual testing as complementary tools to improve safety measures for all aircrew.**

Until recently, aircrew has been mostly 50th to 95th percentile males. Among the military, FAA, NASA, and aircraft, ejection seat, and ATD manufacturers and evaluation teams:

- **The design of aircraft, catapults, helmets, and restraints has focused on the safety of that population.**
- **There exist significant differences in testing, injury evaluation, and protective device selection criteria.**
- **Despite common goals, there have been few efforts toward harmonization.**

Hopefully, the new Aerospace ATD Advisory Group will facilitate harmonization between these entities.

Ejection Catapult Thrust Phase

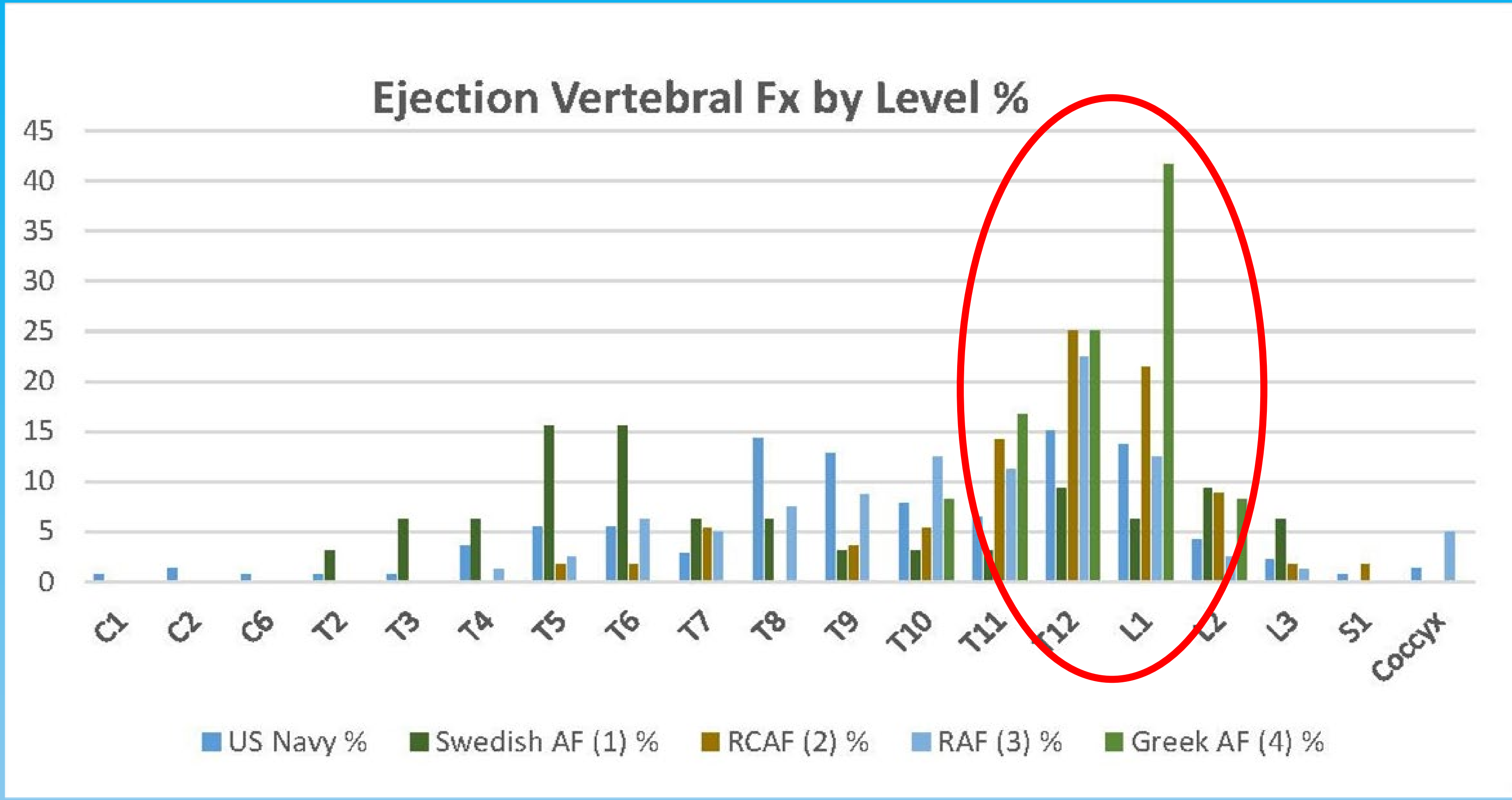
Aircrew experience > 9 G's multi-axial loading

Aircrew spinal injury locations, patterns, and mechanisms are well-documented.

- **Lower neck and thoracolumbar spine compression, burst, and wedge fractures are the prevalent injury patterns.**
- **Pure shear and extension injuries, bilateral dislocations, and unilateral dislocations occur less often.**
- **Upper neck injuries are less likely to occur from ejections.**
- **Spinal injury prediction is often based primarily on upper neck injury metrics (e.g., MANIC).**
- **Lower neck and thoracolumbar spine data are measured, but not utilized in metrics or device selection criteria in many labs.**

Nonfatal Vertebral Ejection Fracture Levels 1958-1969

Ewing, 1971



Ejection Vertebral Fracture Levels 1977-2021

Sommer et al., 2022

TABLE 2. Spine injuries of the included aircrew members

Spine Injury	No. (%)
Fracture	66
C2	3 (4.5%)
C3	1 (1.5%)
C4	1 (1.5%)
C6	2 (3.0%)
T3	2 (3.0%)
T4	1 (1.5%)
T5	2 (3.0%)
T6	2 (3.0%)
T7	2 (3.0%)
T8	7 (10.6%)
T9	2 (3.0%)
T10	5 (7.6%)
T11	9 (13.6%)
T12	12 (18.2%)
L1	12 (18.2%)
L2	1 (1.5%)
L3	2 (3.0%)
Soft-tissue injury	31
Contusion	27 (87%)
Disc protrusion	2 (6.5%)
Disc herniation	
T11–12	1 (3.25%)
L5–S1	1 (3.25%)

66 Vertebral Fxs

Neck: 11% (7)

T-Spine 67% (44)

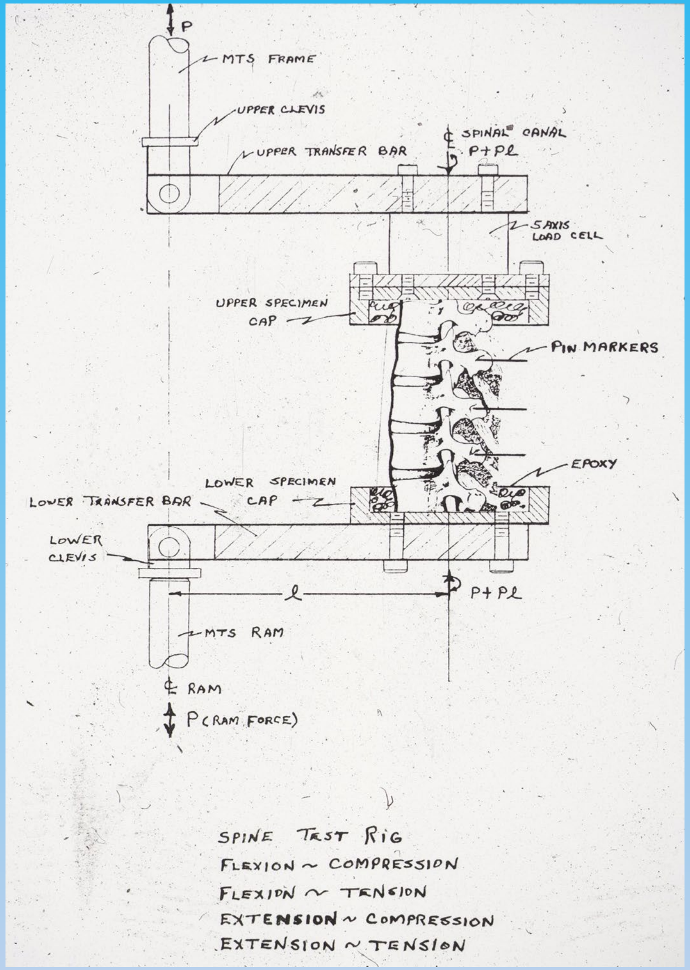
L-Spine 23% (15)

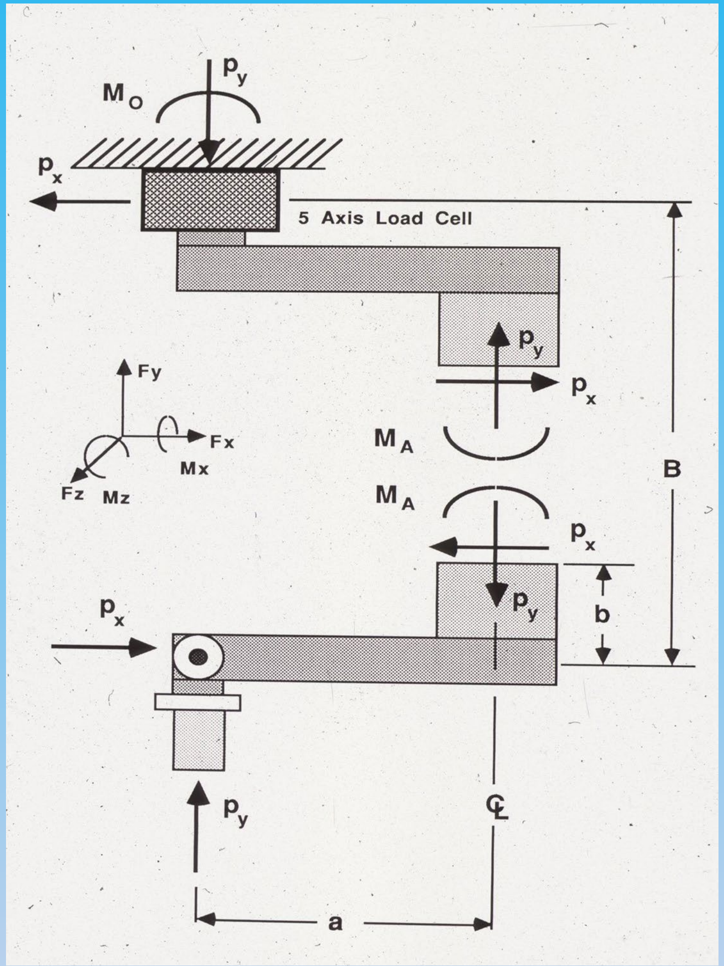
Total aircrew = 103

1.9 fxd vertebra per crew member

Bending Testing at Duke

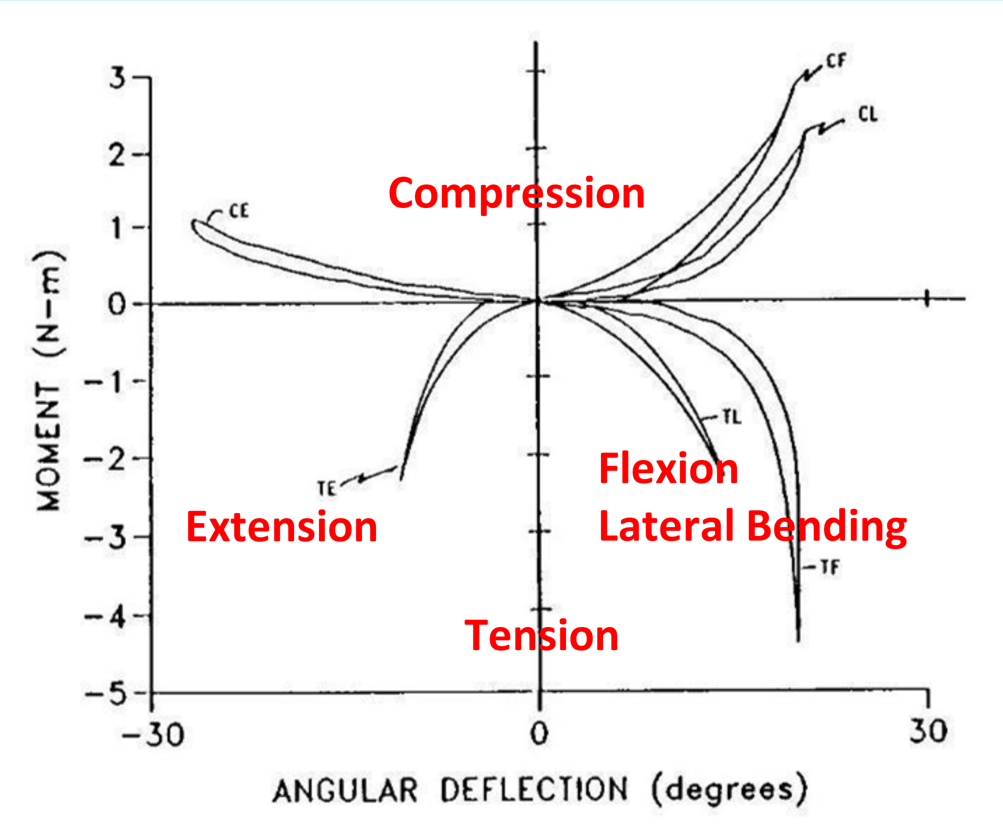
- Controlled NON-INJURY loads were applied to provide data for mathematical models.
- Controlled INJURY-PRODUCING loads were applied to relate the applied loading to the resulting injury patterns and mechanisms.



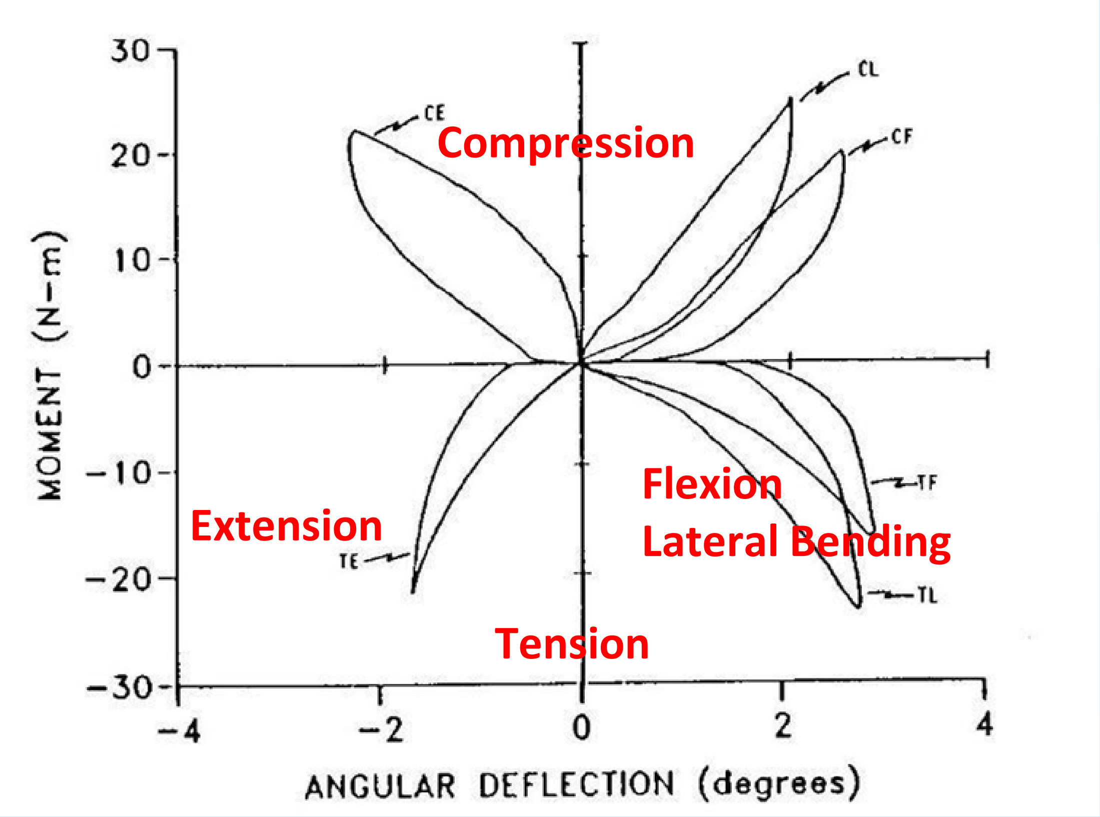


Human v. Hybrid III Cervical Spines in Bending

The Hybrid III ATD neck is far stiffer than the human neck.

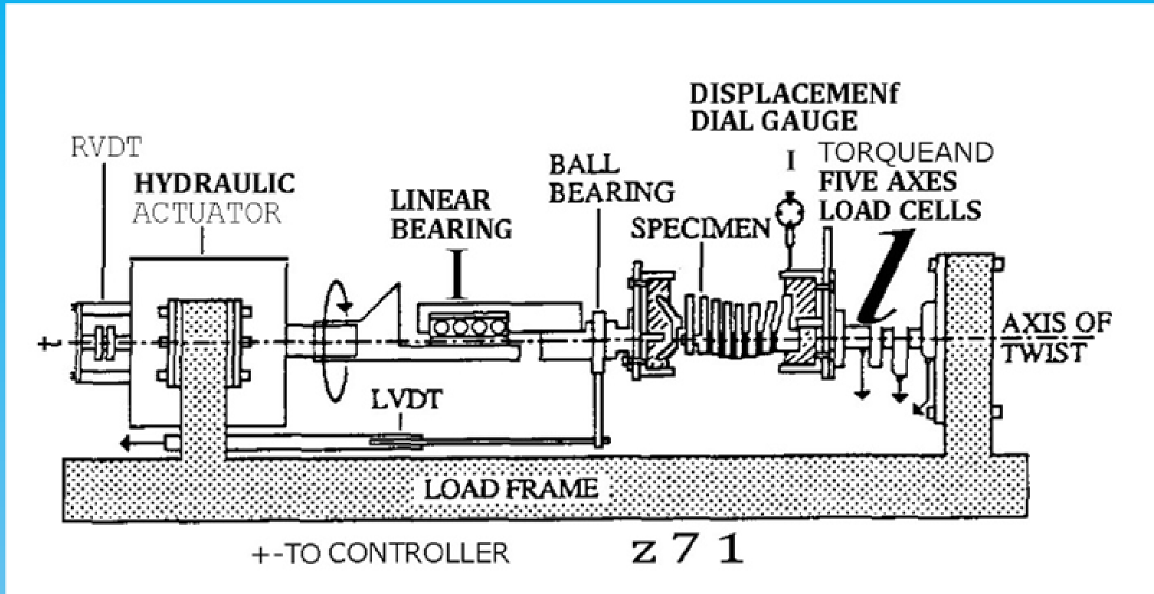


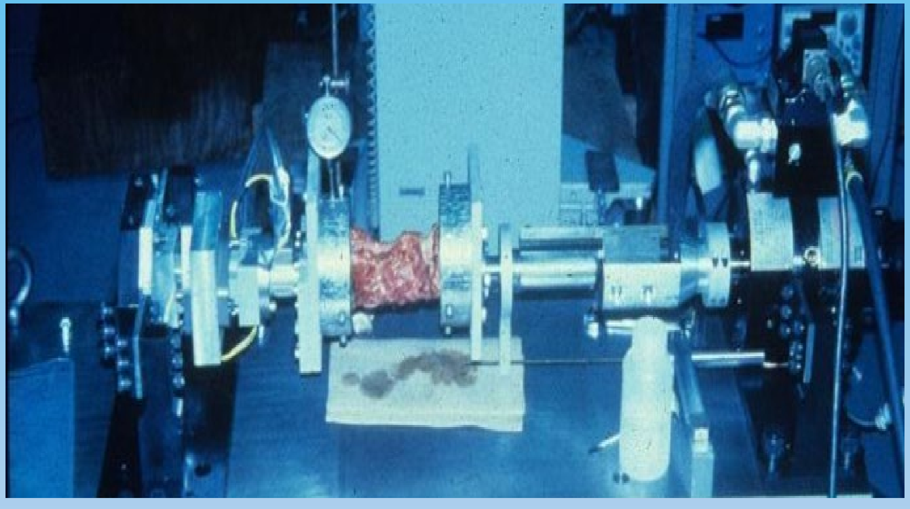
Human

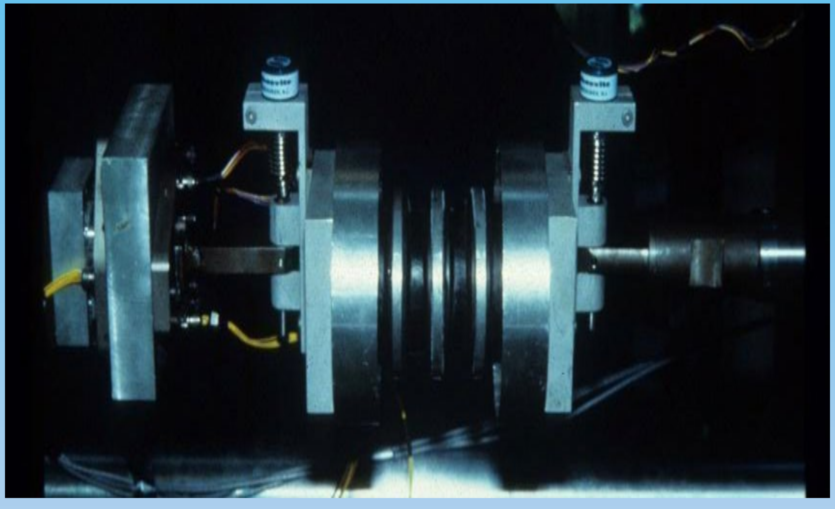


Hybrid III

Human v. H3 Necks in Torsion



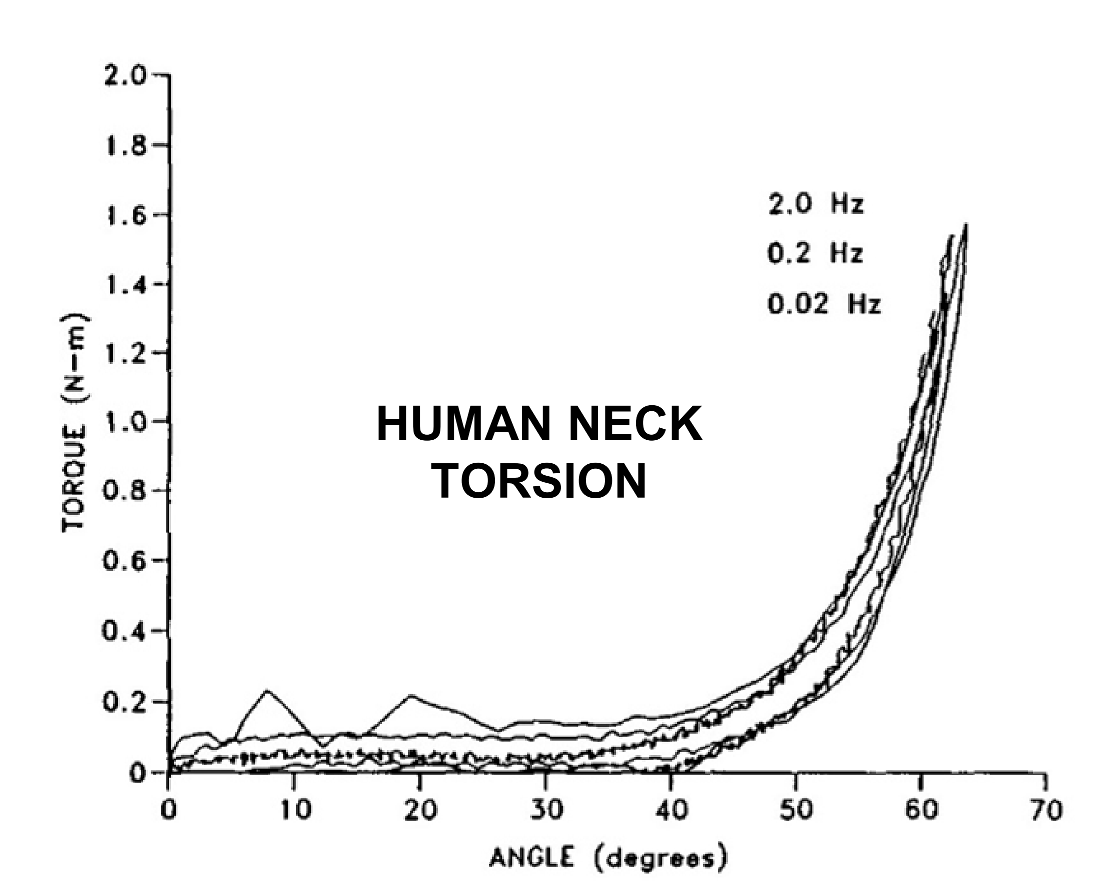


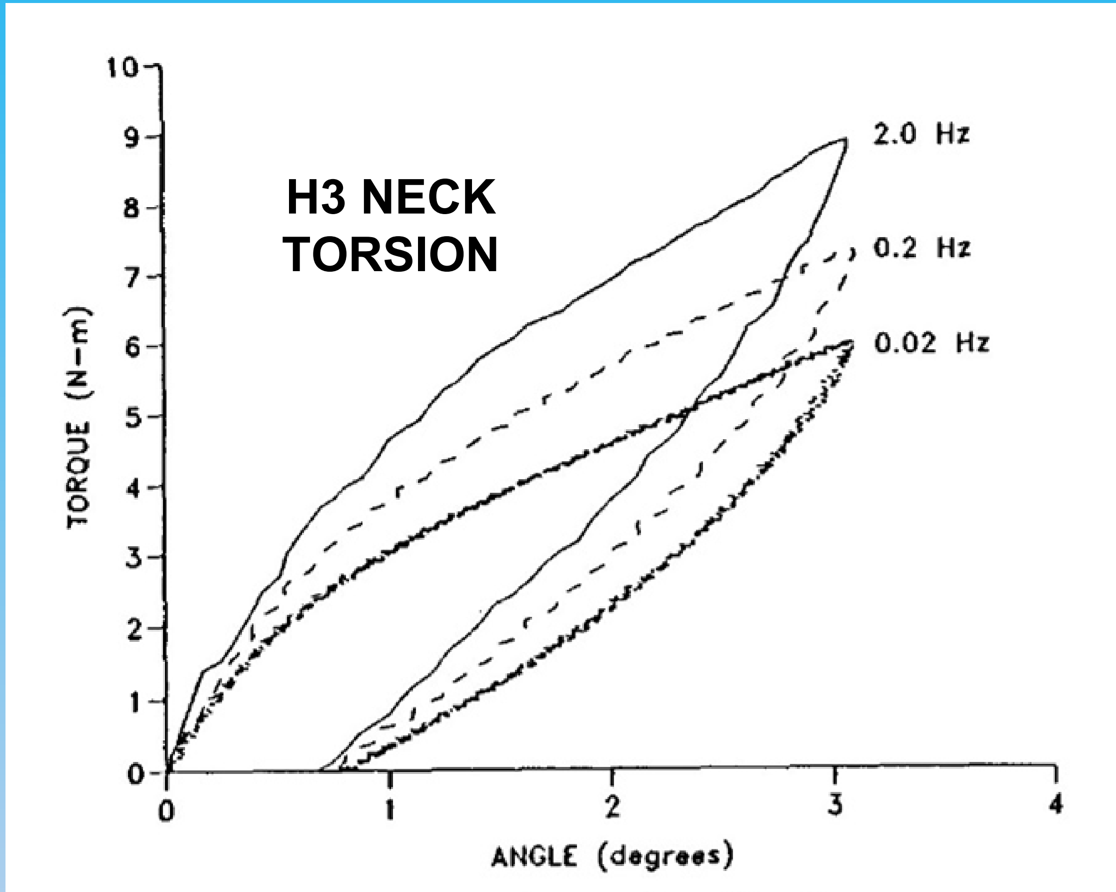


TORSIONAL STIFFNESS: H3 Neck >> HUMAN Neck

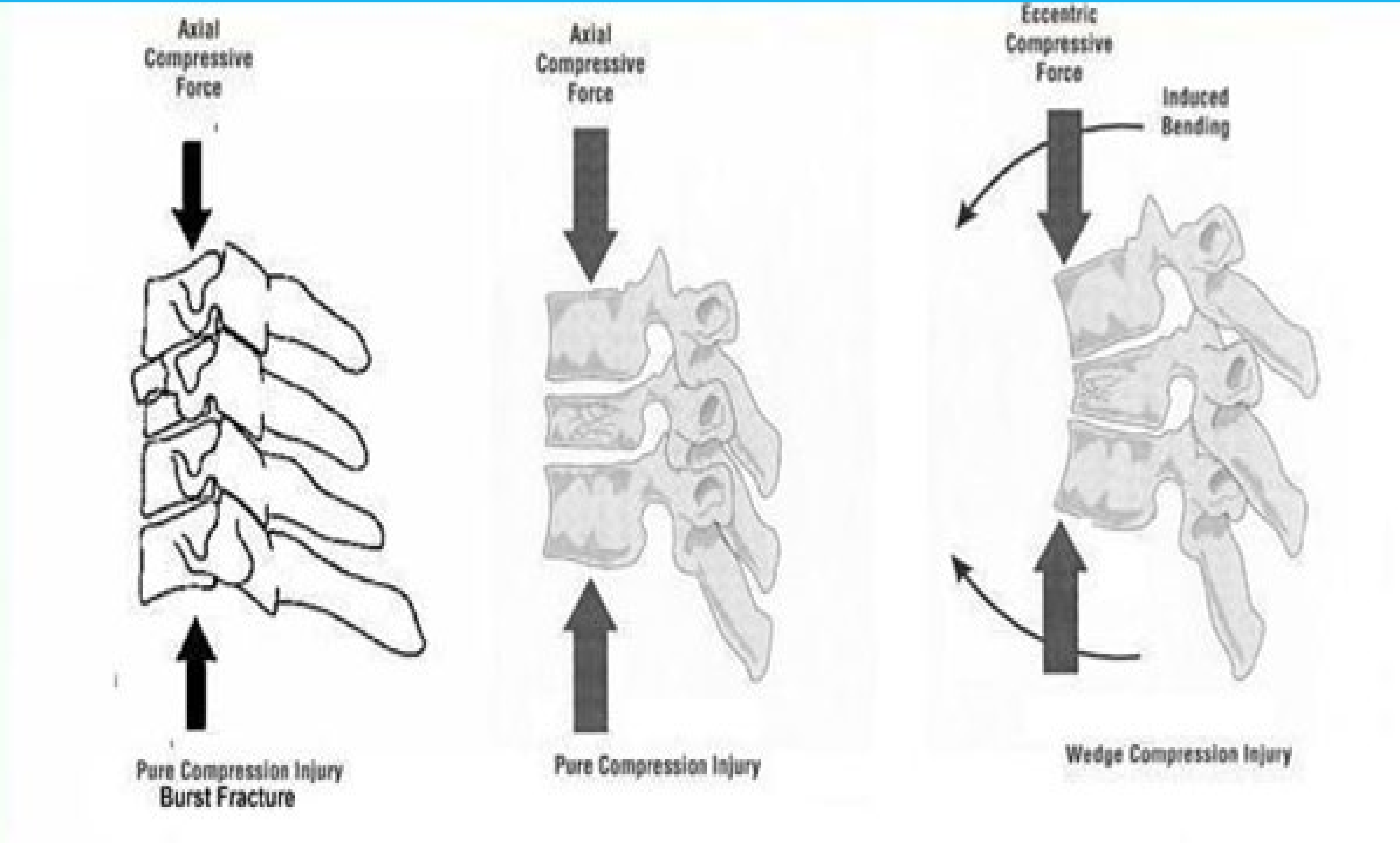
HUMAN NECK: Initial LOW stiffness region <= ~40^o followed by a HIGH stiffness of ~0.5 Nm/^{o} > 40^o

H3 NECK: ~3.2 Nm/^{o} stiffness with NO initial low stiffness region.

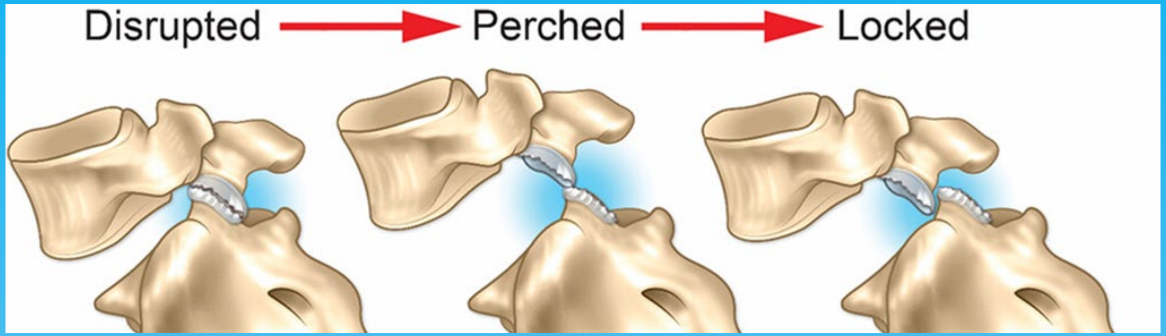


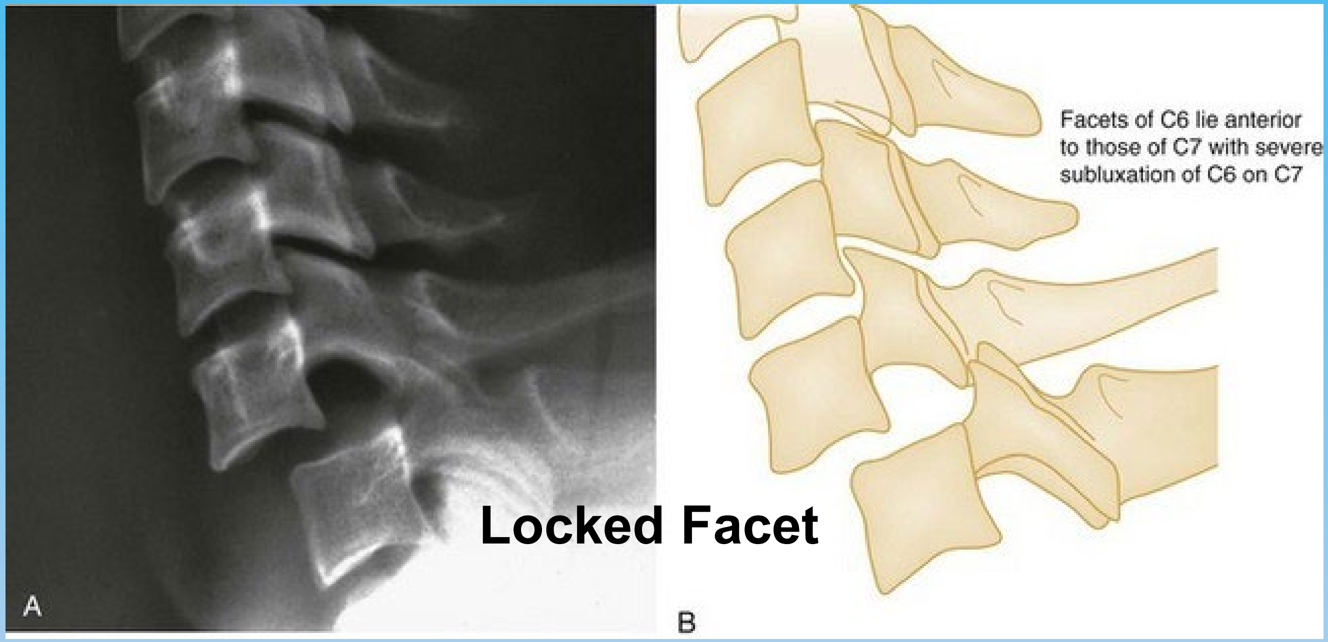


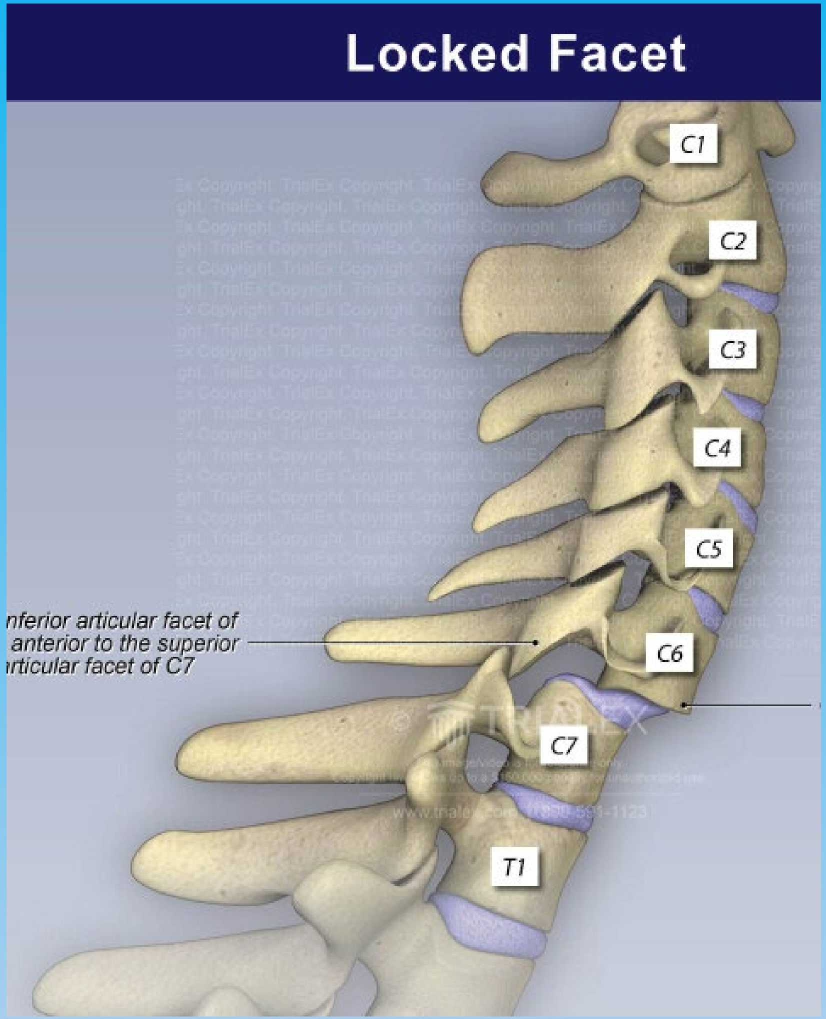
Compression v. Compression-Flexion Fractures



Bilateral Facet Dislocations

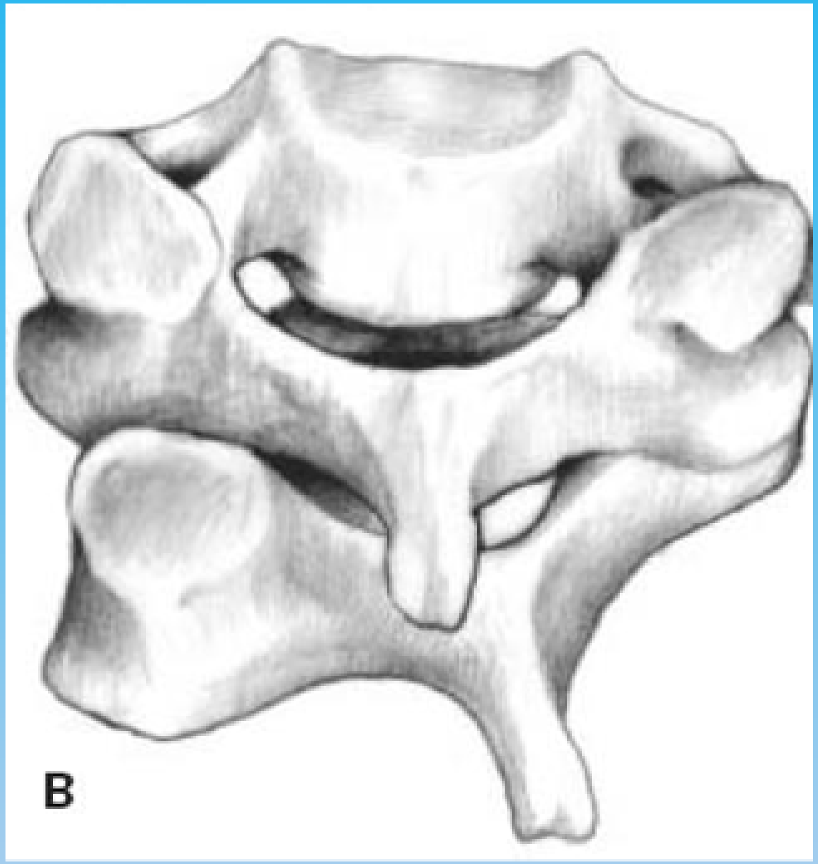




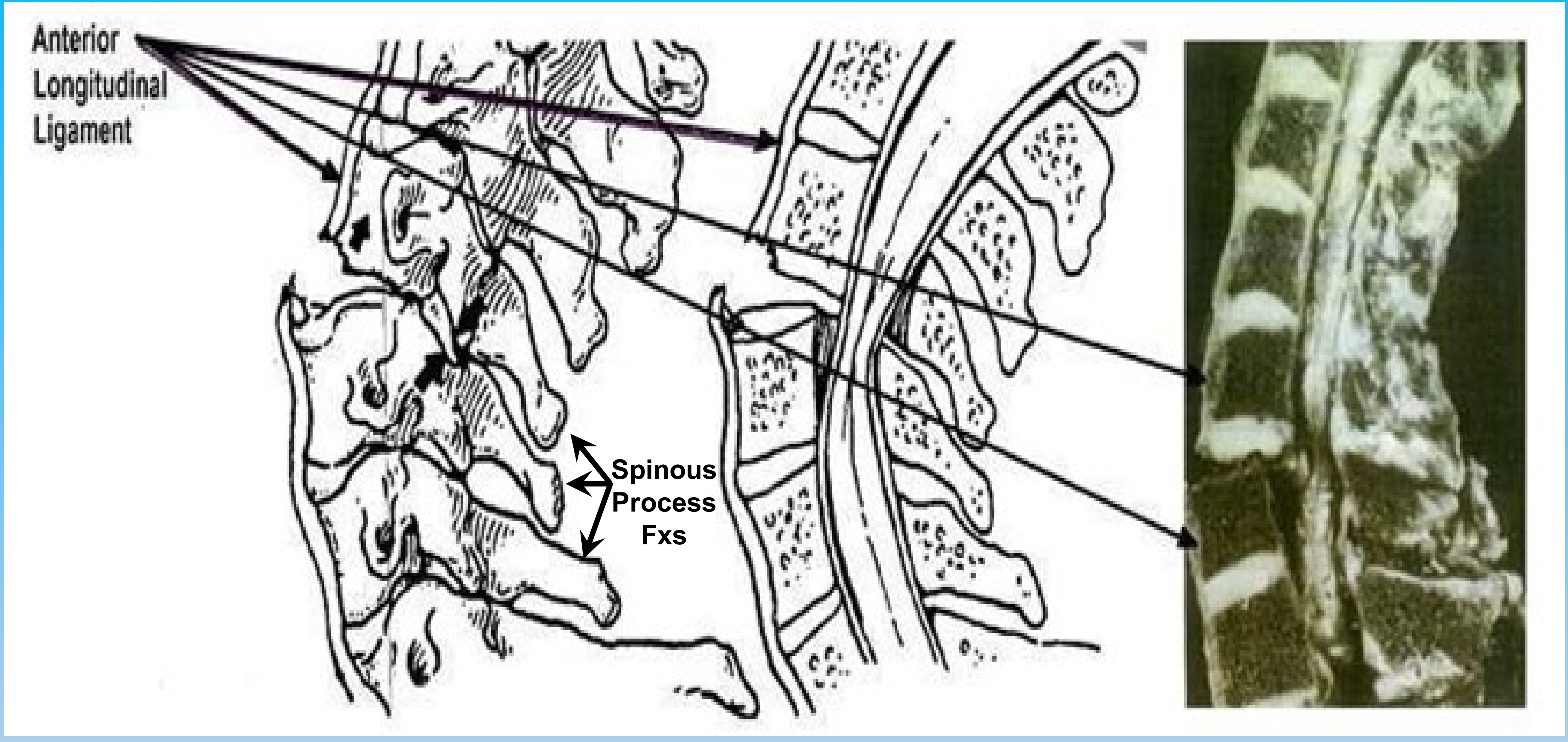


Human Neck Failure in Torsion: Unilateral Facet Dislocation

The human upper neck fails before the lower neck fails.



Extension Injury



Injury Metrics

	Injury Risk	Risk Function	Multi-Axial?	ATD sizes	Location	Validated for HSM
MANIC	5% for AIS>=2	Yes	Axial load, shear, bending, and torsion	5^{th}, 50^{th}, 95^{th}	Upper Neck	YES
NIC	10% for AIS>=3	Yes	Axial load, shear, bending, and torsion	5^{th}, 50^{th}, 95^{th}	Upper and Lower Neck	YES
Nij (NHTSA)	22% for AIS>=2	Yes	Axial load and flexion-extension	5^{th}, 50^{th}, 95^{th}	Upper Neck	NO
Beam Criterion BC	50% for AIS>=2	Yes	Axial load and flexion-extension	50^{th}	Lower Neck	YES
LNic	50% for AIS>1	Yes	Axial load and flexion-extension	5^{th}, 50^{th}, 95^{th}	Lower Neck	N/A
Knox Box	NO	NO	N/A	N/A	N/A	YES
Eiband	5% for AIS>=2	Yes	Axial load	5^{th}, 50^{th}, 95^{th}	Thoracolumbar	YES
DRI	5% for AIS>=2	Yes	Axial load	5^{th}, 50^{th}, 95th	Thoracolumbar	YES
Forces/Moments		Yes	Axial load and flexion-extension		Thoracolumbar	

MANIC was adopted by MIL-HDBK-516, Congress and AFLCMC for ejection systems to maintain: Risk of AIS >= 2 Neck Injury below 5%

MANIC is the spinal injury metric used for protective device selection by the WPAFB lab

Physical v. Virtual Testing to Evaluate Ejection Seats, Helmets, HMDs or NVGs

Physical Testing is important, but often limited in scope due to:

- **Cost (equipment, personnel, instrumentation and ATD maintenance and calibration)**
- **ATD historical changes**
- **Variations related to body positioning, helmet placement, belt tensioning and placement**

Virtual Testing is less costly, less time-consuming, and easily allows parametric studies, but also has limitations.

Aircrew and Surrogates

5th Female, Pregnant Female, 50th Male, 95th Male

- Human Volunteer
- Human Cadaver (PMHS)
- Frontal ATD (FAA, NHTSA Hybrid II, III, THOR)
- Side Impact ATD (SID, Eurosid, WorldSid, Biosid)
- Rear Impact ATD (RID, RID2, Biorid)
- Air Force ATD (GARD, Adam, Lois, Lard)
- Army Blast ATD (Wiaman)

ATDs

Hybrid II	1972
Hybrid III	1976
SID,BIOSID,EUROSID	~1980
ADAM	1984
GARD	<1991
LOIS	<1999
LARD	<1999
THOR	2001
WIAMAN	2011

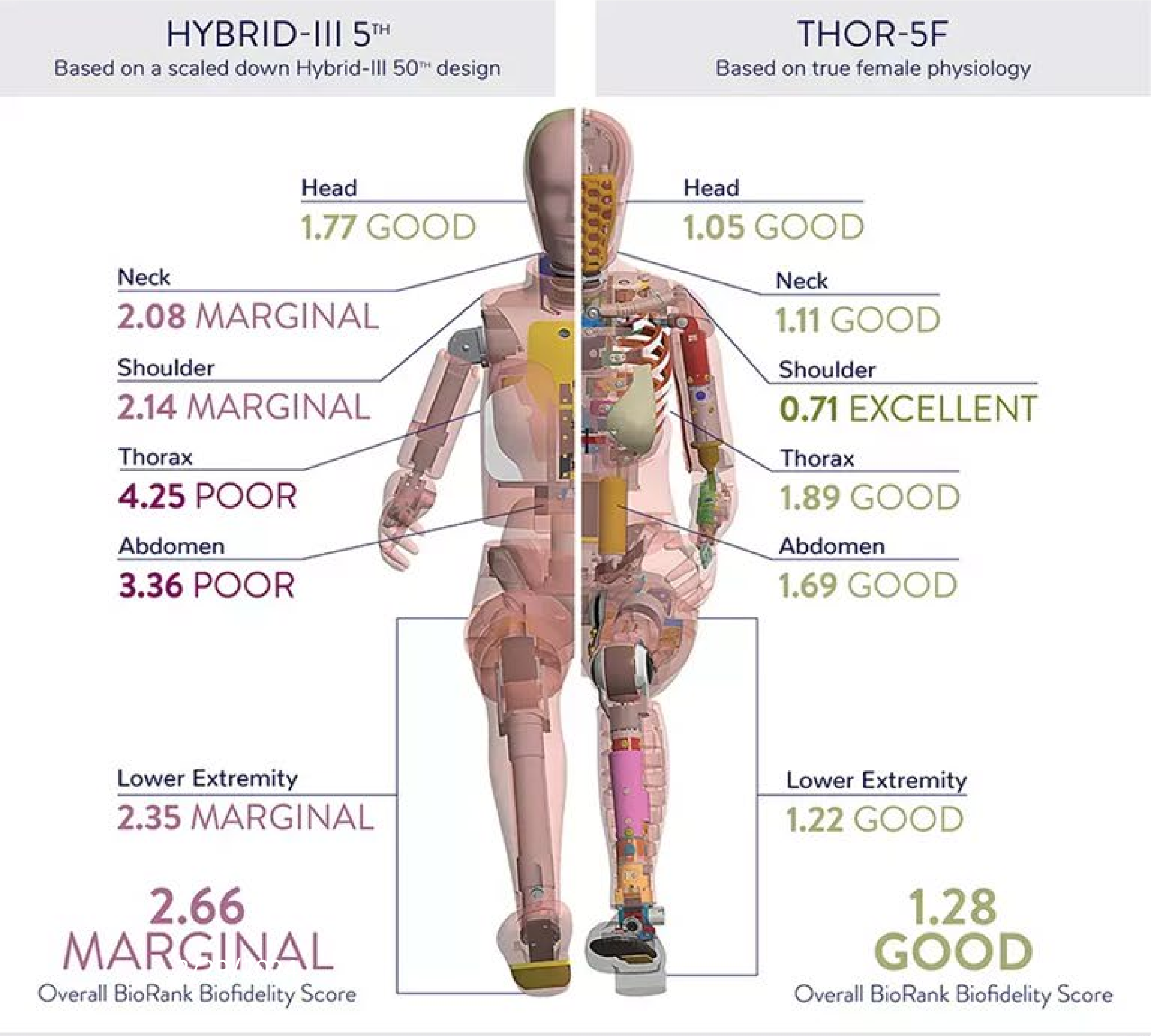
ATD Testing
(are we comparing apples and oranges?)

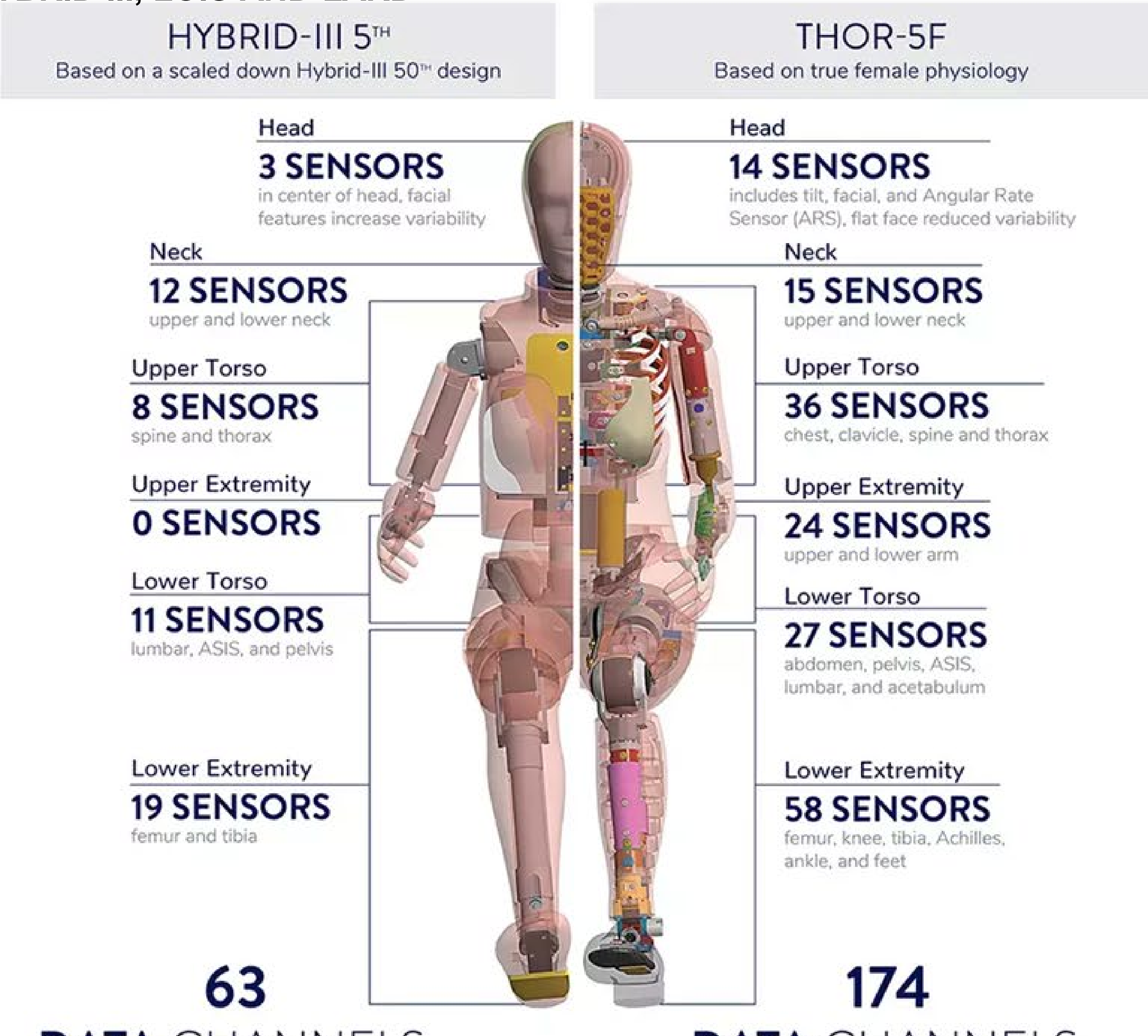
- Biofidelity
  - Lois and Lard may no longer be representative of the current aircrew population
- ATDs like LOIS, LARD, and Hybrid II and III are 20-30 years old
  - degradation is a huge problem due to age or excessive loading
- Historical changes
  - Body parts (e.g., straight v. curved lumbar spines, steel v. aluminum chest box, bronze v. aluminum knees)
  - ATD setup (e.g., fixed v. adjustable lower neck angle bracket to account for bracing)
  - Filtering, instrumentation, and data processing
- Calibration yearly v. when visual problems are identified
- ATD seat storage affecting spine and pelvis response over time
- Neck and lumbar spine rate and temperature sensitivity

ATD BIOFIDELITY RANKING
HYBRID-III 5TH VS THOR-5F

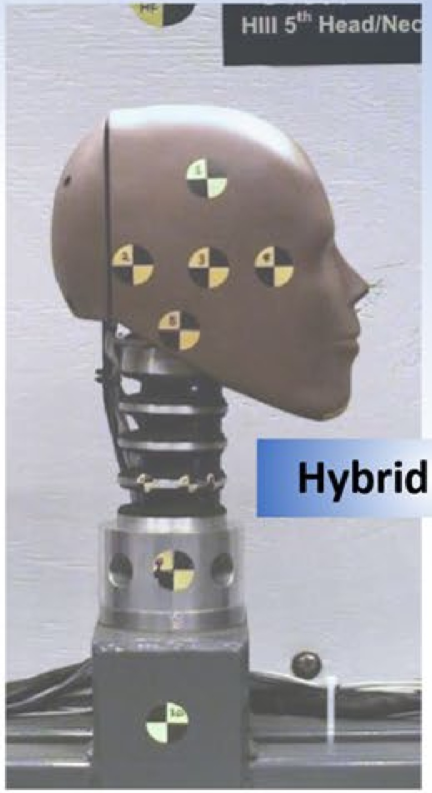
INSTRUMENTATION BY CHANNELS
HYBRID-III 5TH VS THOR-5F

---ALTERNATIVE TO HYBRID III, LOIS AND LARD---





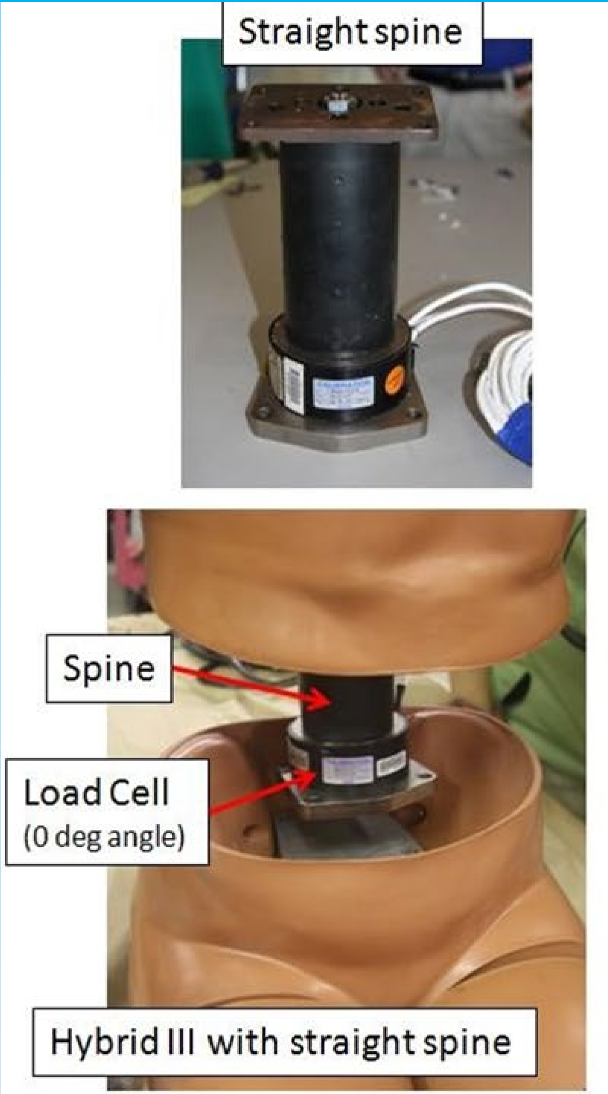
THOR Neck

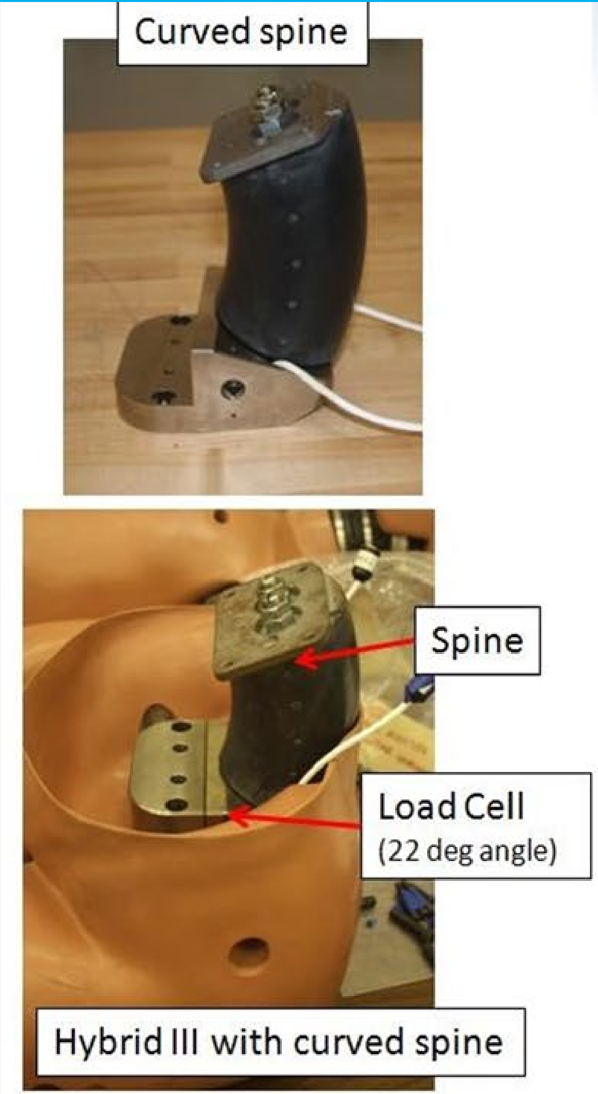


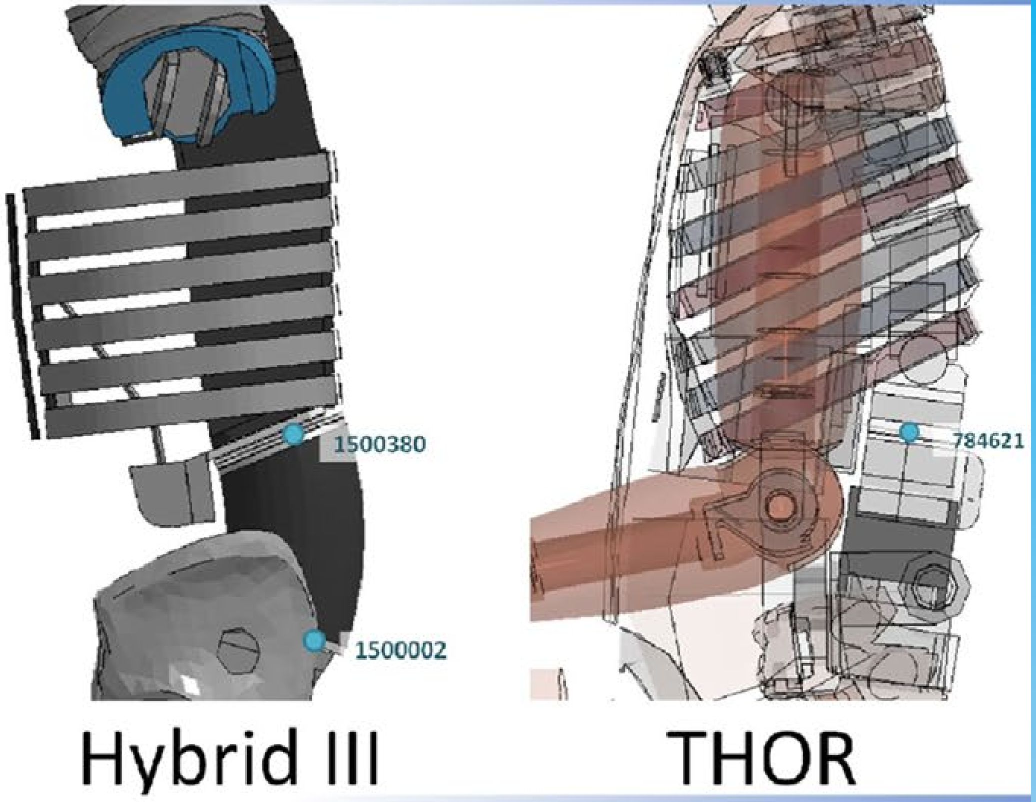
Hybrid III Neck

Hybrid II Neck

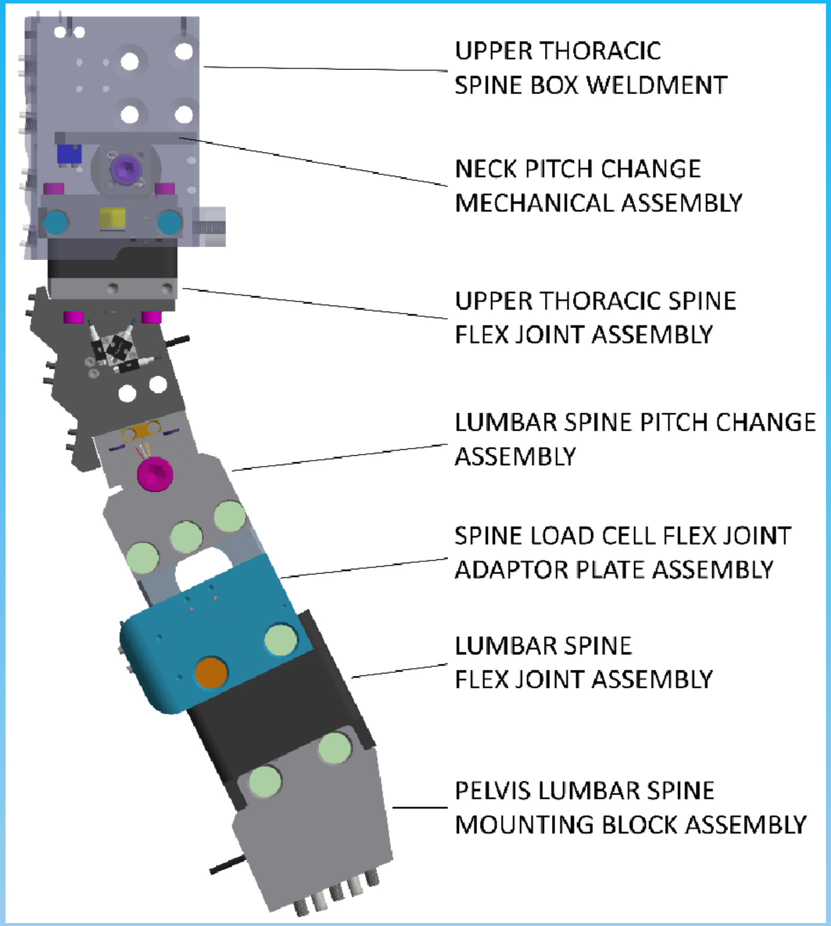
Lumbar Spines



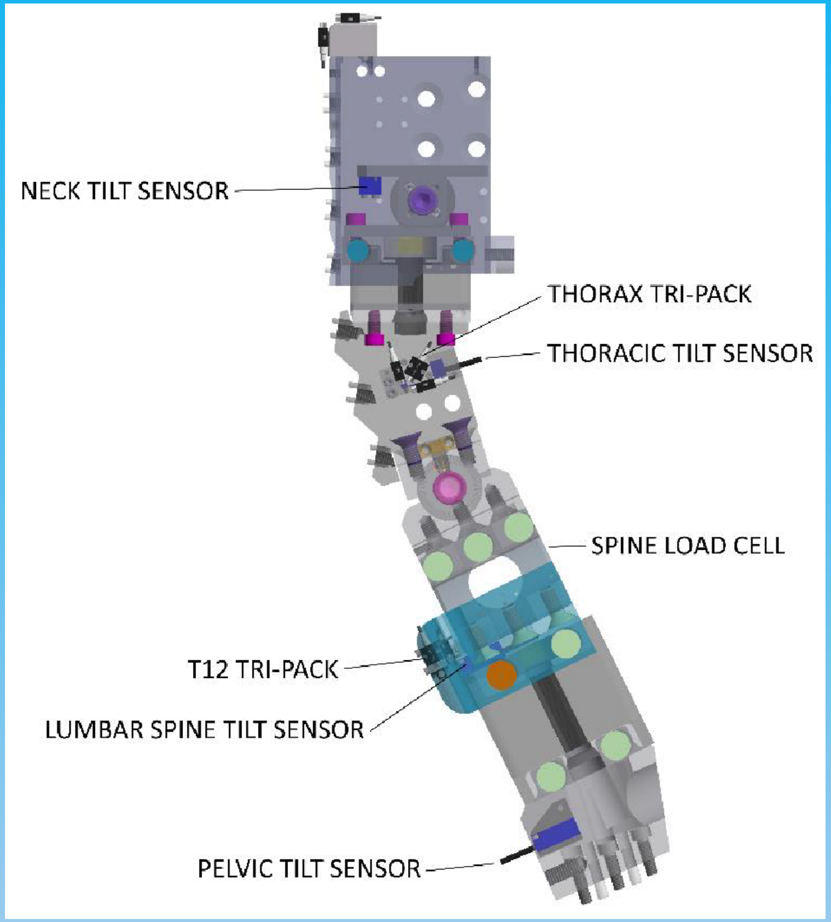




THOR SPINE

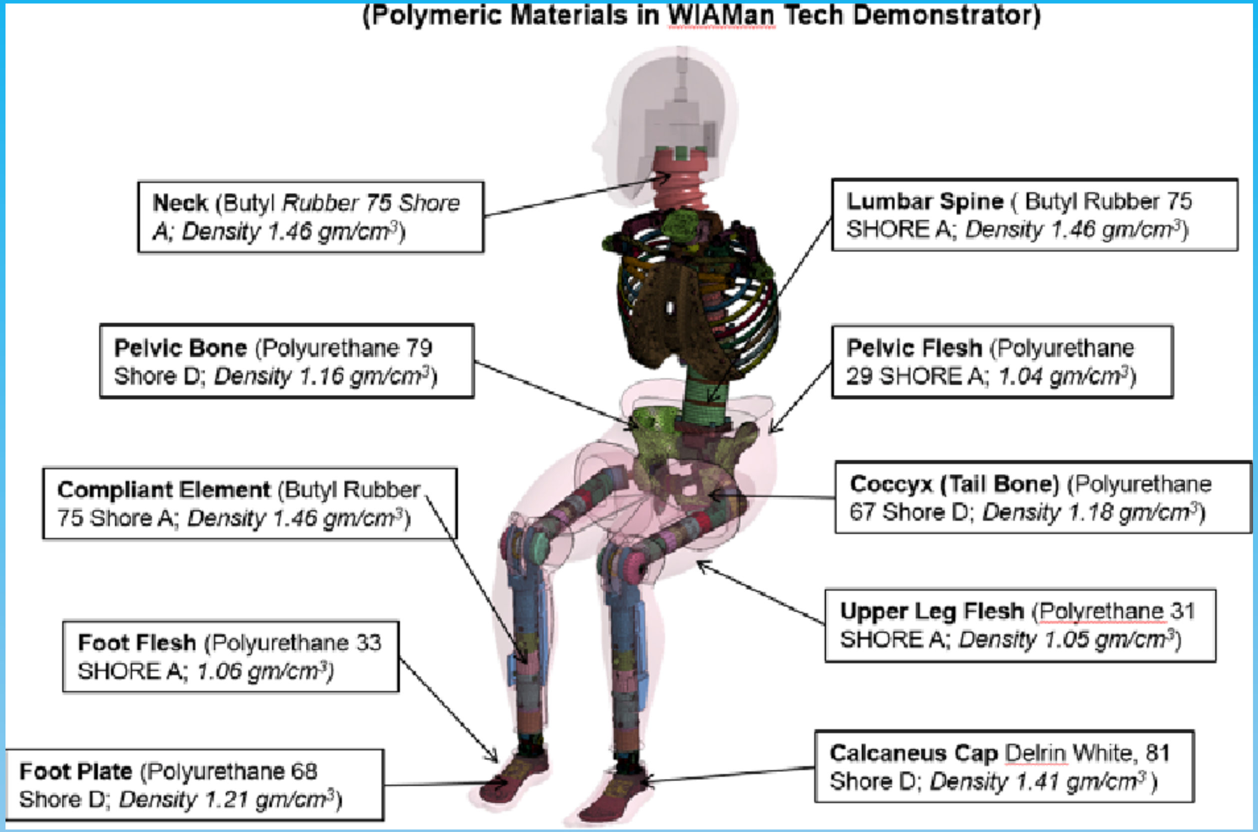


Construction

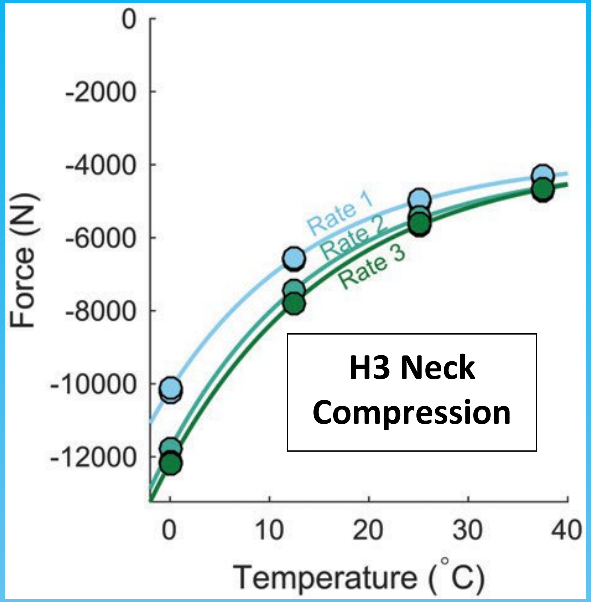


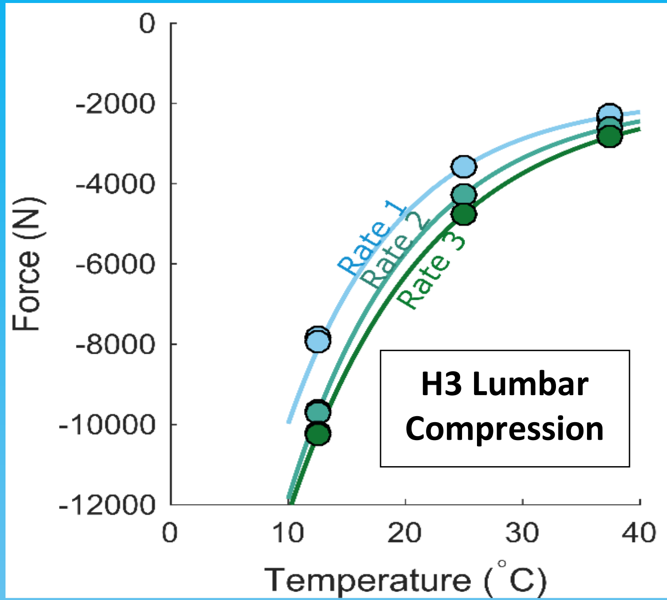
Instrumentation

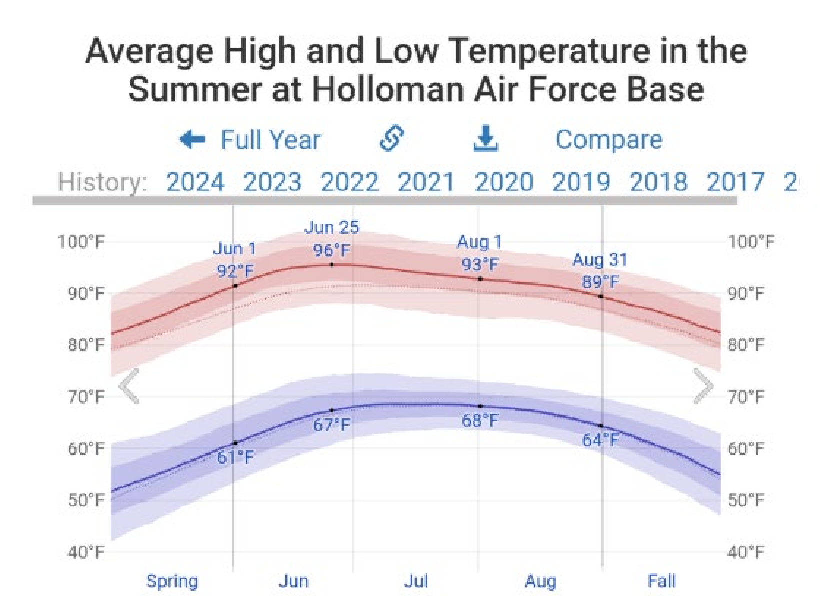
WIAMAN


(Polymeric Materials in WIAMan Tech Demonstrator)
Neck (Butyl Rubber 75 Shore A; Density 1.46 gm/cm³)
Lumbar Spine (Butyl Rubber 75 SHORE A; Density 1.46 gm/cm³)
Pelvic Bone (Polyurethane 79 Shore D; Density 1.16 gm/cm³)
Pelvic Flesh (Polyurethane 29 SHORE A; 1.04 gm/cm³)
Compliant Element (Butyl Rubber 75 Shore A; Density 1.46 gm/cm³)
Coccyx (Tail Bone) (Polyurethane 67 Shore D; Density 1.18 gm/cm³)
Upper Leg Flesh (Polyrethane 31 SHORE A; Density 1.05 gm/cm³)
Foot Flesh (Polyurethane 33 SHORE A; 1.06 gm/cm³)
Foot Plate (Polyurethane 68 Shore D; Density 1.21 gm/cm³)
Calcaneus Cap Delrin White, 81 Shore D; Density 1.41 gm/cm³)

Rate and Temperature Sensitivity of H3 Neck and Lumbar Spine







Temperature had a strong influence on compressive NECK and LUMBAR force and stiffness. Colder temperatures and higher rates were associated with increased force and stiffness.

At the highest rate 3,

- **From 99.5 °F to 32.2 °F, neck compressive force and stiffness doubled.**
- **From 99.5 °F to 54.5 °F, lumbar compressive force and stiffness tripled.**

History of Virtual Testing for Ejection Environments

Modeling complemented with testing were key ejection seat and HSM evaluation tools since the late 1980's, but ONLY testing is used, for example, at WPAFB to approve seats, helmets, etc.

- **The Articulated Total Body (ATB) Model, Dynaman and Madymo lumped-parameter models:**
  - **Obergefell in 1988 predicted aircrew spinal injury potential of helmets and HMDs.**
- **The Head-Spine Model (HSM) used Kazarian's spinal test data:**
  - **Privitzer in 1988 predicted aircrew spinal injury potential of seats, helmets and HMDs.**
- **Matlab**
- **Finite element models (LS-Dyna, GMHBC, THUMS, and VIVA OpenHBM) are considered state-of-the-art occupant kinematics and injury prediction tools.**
  - **Wpafb Pirnstill and FAA Pelletier predicted aircrew responses in aerospace environments**

VIRTUAL TESTING

Software: ATB, HSM, Matlab, LS-Dyna, Thums, GHMBC, OpenHBM

Datasets: Human v. ATD 5th , 50th , 95th Percentile … Frontal, Side, Rear ATDs

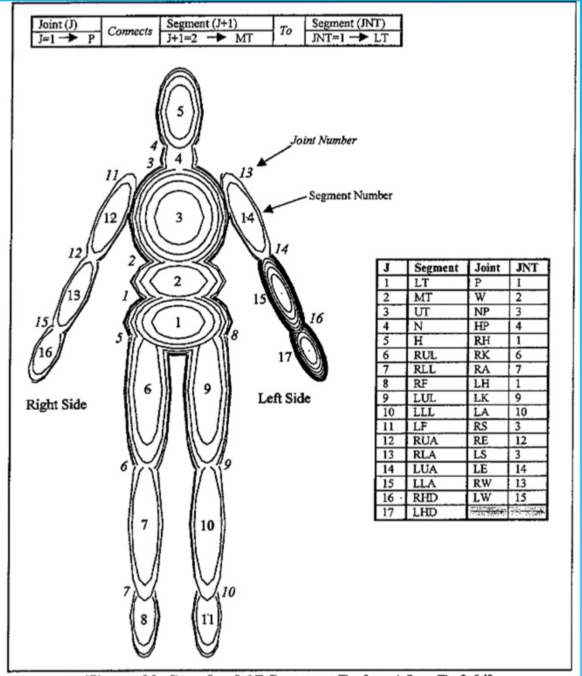
Model Input:

- Acceleration pulse (Gx, Gy, Gz, Mx, My, Mz or combined loading)
- Anthropometry
- Body mass and inertial properties, joint properties, active and/or passive musculature
- Initial body position, braced or not braced
- Seat geometry, stiffness
- Helmet mass, CG, inertial properties
- Restraints geometry, position, mechanical properties, initial tension

Model Output:

- Head-neck kinematics and/or Injury metrics
- Injury patterns and/or Injury mechanisms

Model validation: Volunteer tests, ATD tests, PMHS tests, and/or Real-world data



J	Segment	Joint	JNT
1	LT	P	1
2	MT	W	2
3	UT	NP	3
4	N	HP	4
5	H	RH	1
6	RUL	RK	6
7	RLL	RA	7
8	RF	LH	1
9	LUL	LK	9
10	LLL	LA	10
11	LF	RS	3
12	RUA	RE	12
13	RLA	LS	3
14	LUA	LE	14
15	LLA	RW	13
16	RHD	LW	15
17	LHD	[illegible]	[illegible]

Figure 30. Standard 17 Segment Body. After Ref. [4]

ATB

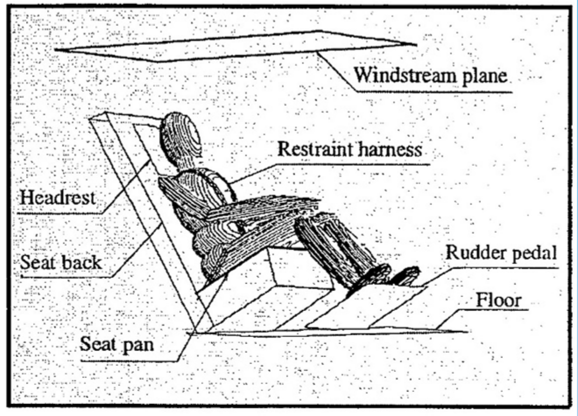


Figure 5. The ACESII-ATB simulation setup.

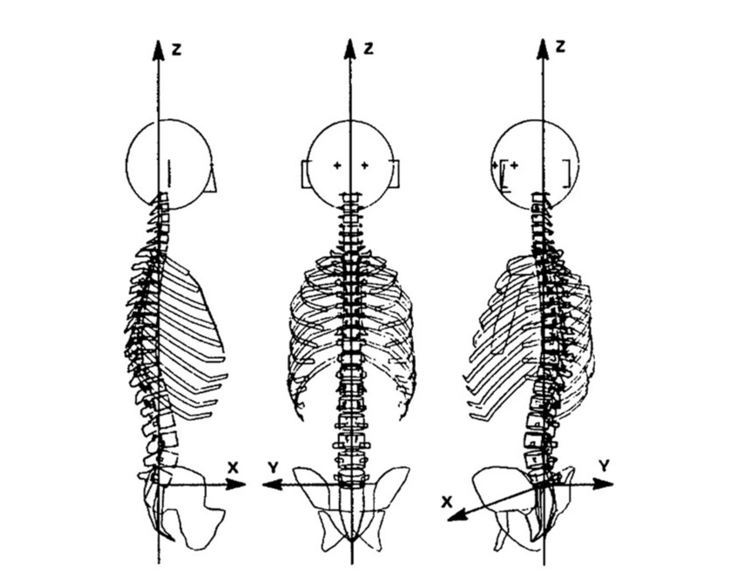
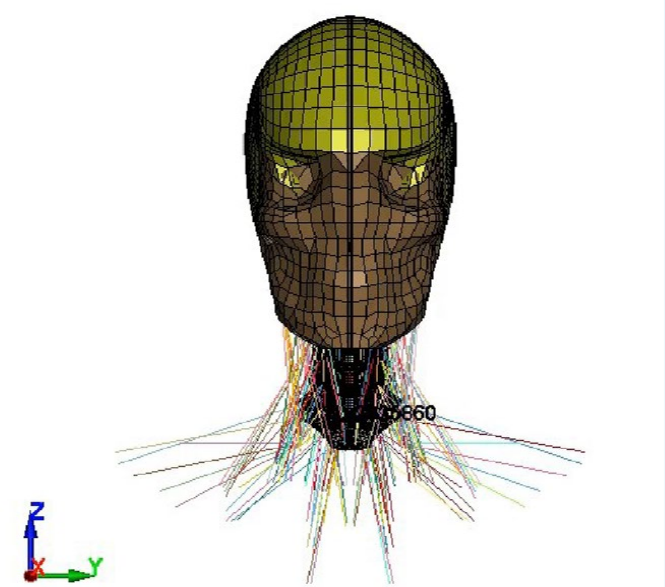
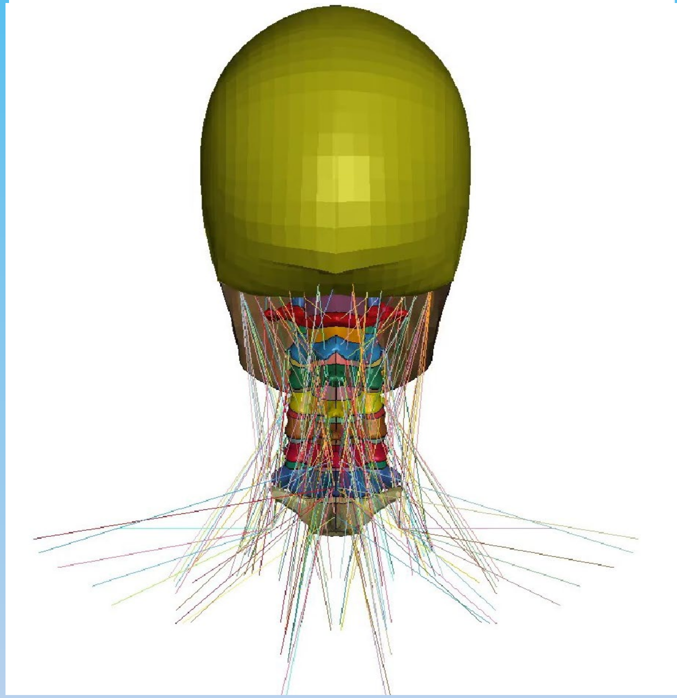


Figure 1. MID-SAGITTAL (X, Z), FRONTAL (Y, Z) AND OBLIQUE VIEWS OF HSM GEOMETRY

HSM



OpenHBM



Virtual Testing

Virtual Testing allows parametric studies to be performed, without test limitations, varying:

- **Input pulses including multiaxial loading**
- **Occupant anthropometry**
- **ATD setup and positioning**
- **Seat and restraint parameters**
- **Helmet, HMD, NVG weights, CGs, and moments of inertia**

Limitations of Virtual Testing:

- **ATD Biofidelity: ATD necks and thoracolumbar spines are much stiffer those of humans.**
- **Data simply does not exist to quantify mechanical properties of every HUMAN neck and thoracolumbar muscle, ligament, and tendon and to model agonistic v. antagonistic functions and active v. passive actions.**
- **Spinal injury potential assessment requires injury metrics, not kinematic responses, at the level of known injuries and representative of known injury mechanisms.**

Aerospace ATD Advisory Group Action Items

Collaboration/harmonization through the creation of the following focus groups:

- **Digital ATDs and Virtual Testing**
  - ➢ **Software**
  - ➢ **Model Input**
  - ➢ **Model Output and Injury Metrics**
- **Physical ATDs and Physical Testing**
  - ➢ **ATD Inventory, Procurement and Calibration**
  - ➢ **Test Facilities and Methodology**
- **Lessons Learned**

CONCLUSIONS

- **Ejection injury patterns and mechanisms are well-documented primarily at the lower neck and thoracolumbar spine more often than at the upper neck.**

- **To account for the known prevalence of lower neck and thoracolumbar spine ejection injuries, metrics at these locations should be included as protective device selection criteria.**

- **Physical and virtual testing are valuable tools protective device evaluation, given limitations.**

- **Collaboration and harmonization could yield the safest ejection environment for our brave male and female aircrew. Hopefully, the Aerospace ATD Advisory Group will facilitate such harmonization.**

THANK YOU!!!!

The Following Slides are for Reference ONLY

Methodology

Applied Loading ⟷ Injury Pattern

Engineers define mechanical determinants that describe the applied loading:

- anthropometry,
- acceleration profile (ejection)
- initial body position
- spinal curvature (e.g., pre-flexed, neutral, pre-extended) to represent the braced v. not braced aircrew
- applied loading direction (e.g., Gx, Gy, Gz, multiaxial), location, angle, eccentricity
- local spinal loading (e.g., compression, tension, bending, shear, torsion), speed/frequency, magnitude
- musculature inactive or active
- seat geometry and stiffness
- restraints geometry, position, mechanical properties, and initial tension

Upper and Lower Neck Injury Metrics

	Neck Injury Risk for AIS	Risk Function	Multi-Axial?	ATD sizes	Upper or Lower Neck	Validated for HSM
MANIC	5% for AIS>=2	Yes	Axial load, shear, bending, and torsion	5th, 50th, 95th	Upper Neck	YES
NIC	10% for AIS>=3	Yes	Axial load, shear, bending, and torsion	5th, 50th, 95th	Upper and Lower Neck	YES
Nij (NHTSA)	22% for AIS>=2	Yes	Axial load and flexion-extension	5th, 50th, 95th	Upper Neck	NO
Beam Criterion BC	50% for AIS>=2	Yes	Axial load and flexion-extension	50th	Lower Neck	YES
LNic	50% for AIS>1	Yes	Axial load and flexion-extension	5th, 50th, 95th	Lower Neck	N/A
Knox Box	NO	NO	N/A	N/A	N/A	YES

Upper Neck MANIC is the metric used to predict spinal injury in the WPAFB lab

Upper Neck MANIC

$$MANIC = \sqrt{\left(\frac{F_X}{F_{Xcrit}}\right)^2 + \left(\frac{F_Y}{F_{Ycrit}}\right)^2 + \left(\frac{F_Z}{F_{Zcrit}}\right)^2 + \left(\frac{M_Y}{M_{Ycrit}}\right)^2 + \left(\frac{M_Z}{M_{Zcrit}}\right)^2}$$

Where:

Fx = observed x direction shear loading
Fxcrit = critical intercept value for x direction shear loading
Fy = observed y direction shear loading
Fycrit = critical intercept value for y direction shear loading
Fz = observed axial loading (+*Fz* = tension, -*Fz* = compression)
Fzcrit = critical intercept value for axial loading (different for tension/compression)
Mx = observed moment about the anatomical x axis (side bending)
Mxcrit = critical intercept value for side bending
My = observed moment about the anatomical y axis (sagittal plane anterior/posterior bending, +*My* = flexion, -*My* = extension)
Mycrit = critical intercept value for sagittal plane moments (different for flexion/extension)
Mz = observed moment about the anatomical z axis (neck twisting)
Mzcrit = critical intercept value for neck twisting

Upper Neck MANIC

MANIC criteria were adopted by MIL-HDBK-516, and consistent with Congressional and AFLCMC limits for ejection systems to maintain:

Risk of AIS >= 2 Neck Injury below 5%

MANIC is the metric used to predict spinal injury in the WPAFB lab

Manikin Neck Size	Manikin Mass	Human Mass	Component	Force		Component	Moment	
	(lbs)	(lbs)		(lbs)	(N)		(in-lbs)	(N-m)
Small Female Hybrid III (for 103-135 pound manikin)	103	<114	F_{xcrit}	405	1802	M_{xcrit}	593	67
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	872	3880	M_{zcrit}		
			$+F_{zcrit}$ (tens)	964	4287	$+M_{ycrit}$ (flex)	1372	155
	125	114-130.5	F_{xcrit}	496	2206	M_{xcrit}	845	95
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1099	4889	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1214	5400	$+M_{ycrit}$ (flex)	1939	219
	136	130.5-143	F_{xcrit}	522	2322	M_{xcrit}	912	103
			F_{ycrit}			$-M_{ycrit}$ (extens)		
Mid Male Hybrid III (for 136-199 pound manikin)			$-F_{zcrit}$ (comp)	1157	5147	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1278	5685	$+M_{ycrit}$ (flex)	2094	237
	150	143-161	F_{xcrit}	561	2495	M_{xcrit}	1016	115
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1243	5529	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1373	6107	$+M_{ycrit}$ (flex)	2333	264
	172	161-186	F_{xcrit}	625	2780	M_{xcrit}	1195	135
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1385	6160	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1530	6806	$+M_{ycrit}$ (flex)	2744	310
	200	186-210	F_{xcrit}	683	3038	M_{xcrit}	1364	154
			F_{ycrit}			$-M_{ycrit}$ (extens)		
Large Male Hybrid III (for 200-245 pound manikin)			$-F_{zcrit}$ (comp)	1513	6730	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1671	7433	$+M_{ycrit}$ (flex)	3133	354
	220	210-232.5	F_{xcrit}	777	3456	M_{xcrit}	1584	179
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1673	7440	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1847	8216	$+M_{ycrit}$ (flex)	3673	415
	245	232.5+	F_{xcrit}	836	3719	M_{xcrit}	1850	209
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1853	8243	M_{zcrit}		
			$+F_{zcrit}$ (tens)	2047	9106	$+M_{ycrit}$ (flex)	4248	480

Nij

The Normalized Neck Injury Criterion Nij considers axial forces and sagittal plane A-P bending moments

- **NTE (tension-extension) and NTF (tension-flexion),**
- **NCE (compression-extension) and NCF (compression-flexion)**

where the "ij" subscripts of the Nij:

- **T and C represent the axial tension and compression force index, respectively**
- **F and E represent the sagittal plane flexion and extension bending moment index, respectively.**

The Nij is the sum of the normalized loads and moments:

$$Nij = \frac{F_z}{F_{zc}} + \frac{M_{OCy}}{M_{yc}}$$

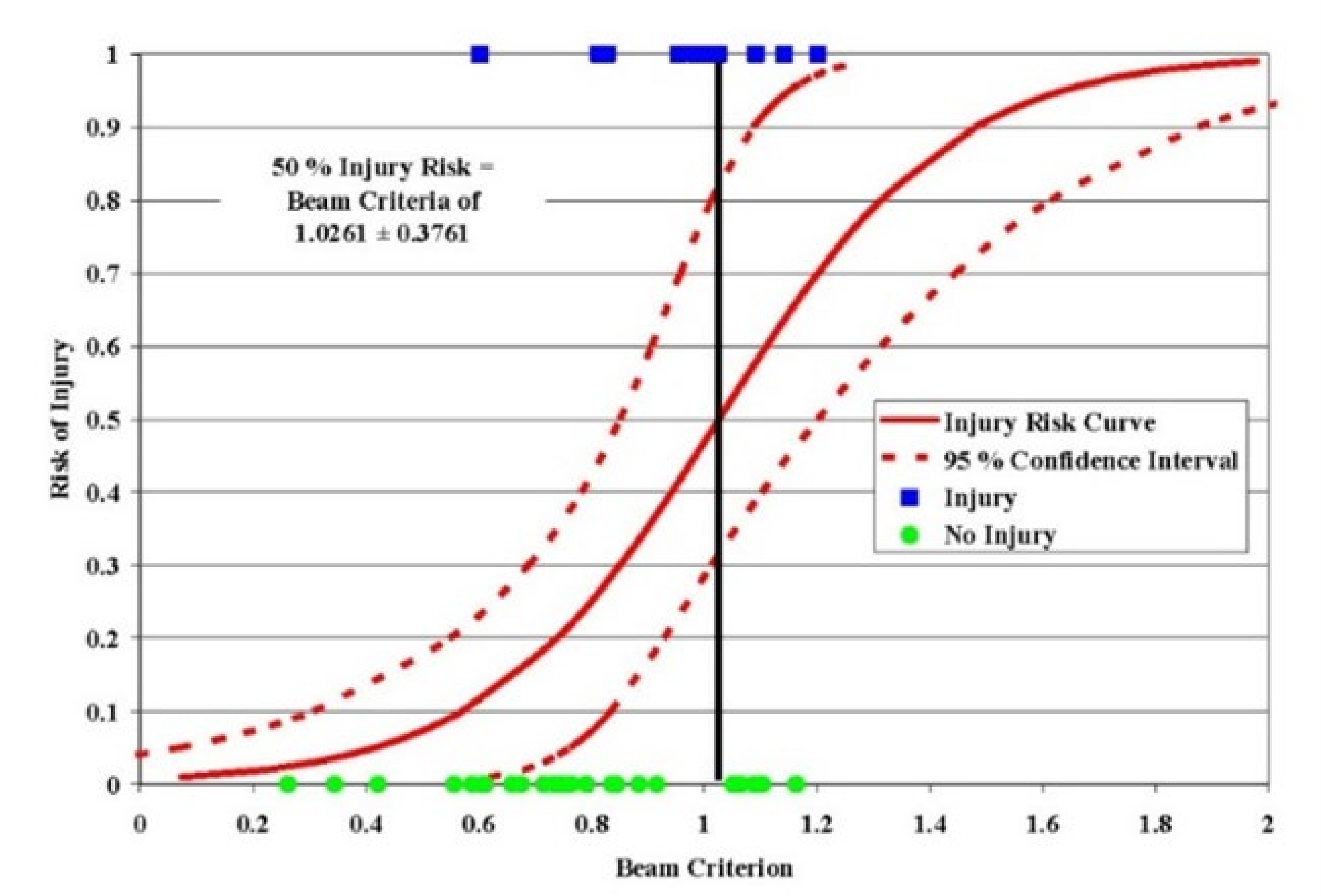
where:

F_z	**axial force at the OC**
M_{OCy}	**flexion-extension bending moment at the OC**
F_{zc}	**Critical axial force intercept value used for normalization**
M_{yc}	**Critical flexion-extension bending moment intercept value used for normalization.**

The current Nij "performance limit" is set at 1.0. A test where Nij>1 fails the criterion.

Lower Neck
Beam Criterion

$$BC = \frac{F_Z}{F_{ZC}} + \frac{M_Y}{M_{YC}}$$



where:

- F_z is the axial compression-tension neck force at the C7-T1 intervertebral disc
- M_Y is the A-P flexion-extension moment in the sagittal plane at the C7-T1 intervertebral disc
- F_{ZC} is critical axial force
- M_{YC} is the critical moment

Optimized IARC (mean BC =1 .0 and SD= 0.38) corresponds to 50% risk of AIS ≥ 2 Lower Neck Injury

- ***Optimized*** F_{ZC} **= 5660 N in axial tension**
- ***Optimized*** F_{ZC} **= 5430 N in axial compression**
- ***Optimized*** M_{YC} **= 141 Nm in A-P flexion**

Lower Neck NIC

10% Risk of AIS >= 3 Injury

Table 4. NIC Summary (from Nichols, 2006)

Criteria Element	Upper Neck Limit	Lower Neck Limit
1) Tension Duration S – small (0-135 lb) M – medium (136-199 lb) L – large (200+ lb)	**S** (5 ms, 414 lbs 31 ms, 414 lbs 40 ms, 200 lbs 80 ms, 200 lbs) **M** (5 ms, 618 lbs 35 ms, 618 lbs 45 ms, 320 lbs 80 ms, 320 lbs) **L** (5 ms, 761 lbs 37 ms, 761 lbs 48 ms, 450 lbs 80 ms, 450 lbs)	Same
2) Compression Duration S – small (0-135 lb) M – medium (136-199 lb) L – large (200+ lb)	**S** (5 ms, 519 lbs 27 ms, 200 lbs 80 ms, 200 lbs) **M** (5 ms, 790 lbs 30 ms, 320 lbs 80 ms, 320 lbs) **L** (5 ms, 979 lbs 32 ms, 450 lbs 80 ms, 450 lbs)	Same
3) Shear (composite) Duration S – small (0-135 lb) M – medium (136-199 lb) L – large (200+ lb)	**S** (5 ms, 405 lbs 20 ms, 225 lbs 29 ms, 225 lbs 37 ms, 165 lbs 80 ms, 165 lbs) **M** (5 ms, 625 lbs 25 ms, 337 lbs 35 ms, 337 lbs 45 ms, 247 lbs 80 ms, 247 lbs) **L** (5 ms, 777 lbs 28 ms, 414 lbs 39 ms, 414 lbs 50 ms, 304 lbs 80 ms, 304 lbs)	**S** (5 ms, 810 lbs 20 ms, 450 lbs 29 ms, 450 lbs 37 ms, 330 lbs 80 ms, 330 lbs) **M** (5 ms, 1250 lbs 25 ms, 674 lbs 35 ms, 674 lbs 45 ms, 494 lbs 80 ms, 494 lbs) **L** (5 ms, 1554 lbs 28 ms, 828 lbs 39 ms, 828 lbs 50 ms, 608 lbs 80 ms, 608 lbs)
4) $N_{ij} = \frac{F_z}{F_{zcrit}} + \frac{M_y}{M_{ycrit}}$ (S / M / L) $+F_{zcrit}$ (lb): 964 / 1530 / 1847 $-F_{zcrit}$ (lb): 872 / 1385 / 1673 $+M_{ycrit}$ (in-lb): 1372 / 2744 / 3673 $-M_{ycrit}$ (in-lb): 593 / 1195 / 1584	Peak *Nij* < 0.5	Peak *Nij* < 1.5
5) $NMI_x = \frac{M_x}{M_{xLIM}}$ $+/-M_{xLIM}$(in-lb): 593 / 1195 / 1584	Peak $NMI_x < 0.5$	Peak $NMI_x < 1.5$
6) $NMI_z = \frac{M_z}{M_{zLIM}}$ $+/-M_{zLIM}$ (in-lb): 593 / 1195 / 1584	Peak $NMI_z < 0.5$	Peak $NMI_z < 1.0$

UNCLASSIFIED

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL REPORT

REPORT NO: NAWCADPAX/TR-2004/86

CERVICAL INJURY RISK RESULTING FROM ROTARY WING IMPACT:
ASSESSMENT OF INJURY BASED UPON AVIATOR SIZE, HELMET MASS PROPERTIES, AND IMPACT SEVERITY

by

Glenn Paskoff

21 October 2004

Crew Systems Bulletin

AFLCMC/EZFC
Bldg 28, 2145 Monhan Way
WPAFB, OH 45433-7017
Phone 937-656-9683

Number: EZFC-CSB-16-001

Date: 28 Nov 2016

Subject: USAF Revision of MIL-HDBK-516C section 9.1.1Escape system safety compatibility criteria standard; supporting data and legacy criteria.

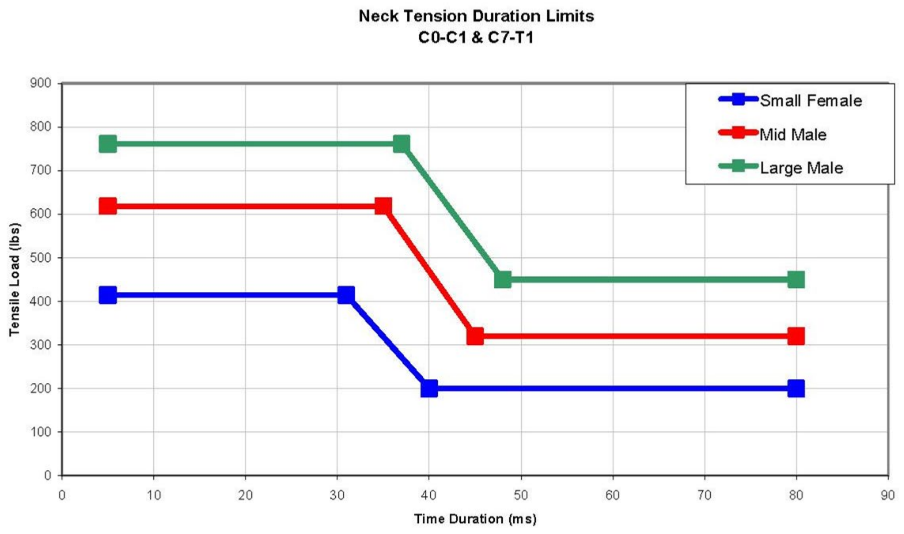


Figure G-1: Neck Tension Duration Limits (C0-C1 and C7-T1)

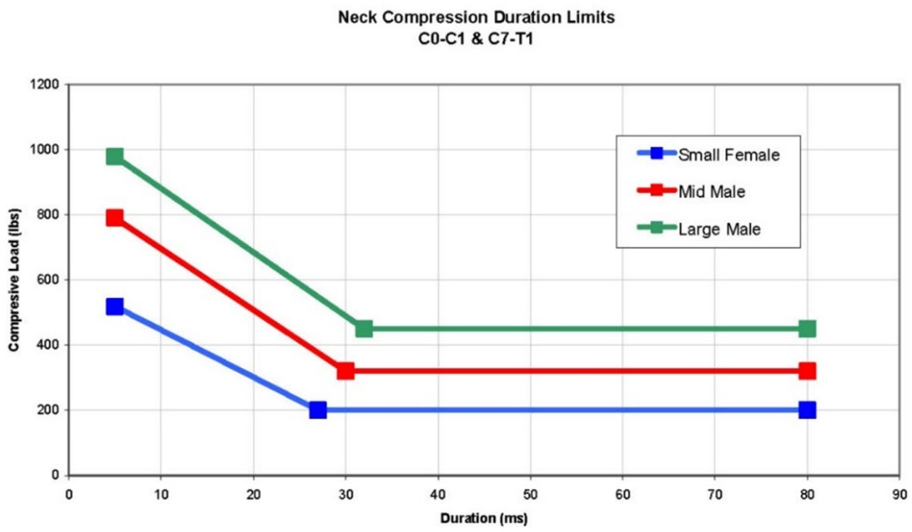


Figure G-2: Neck Compression Duration Limits (Co-C1 and C7-T1)

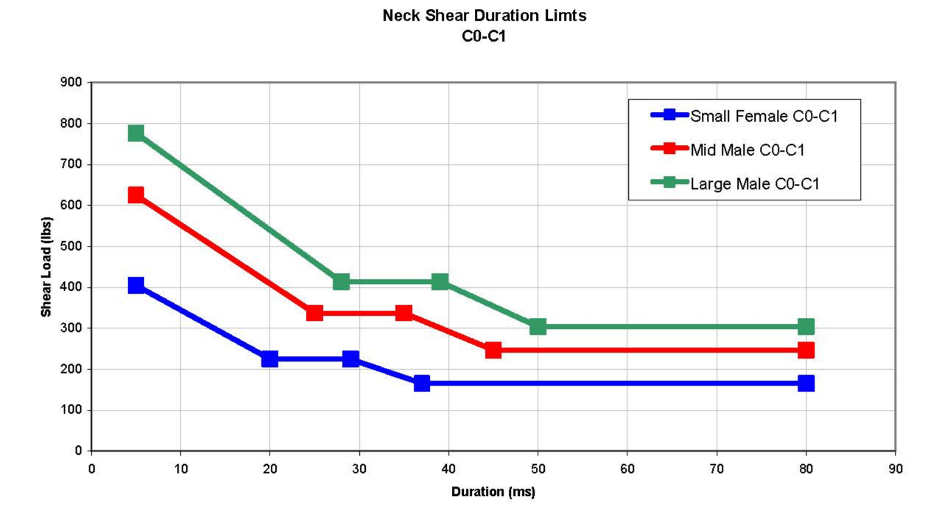


Figure G-3: Neck Shear Duration Limits (C0-C1)

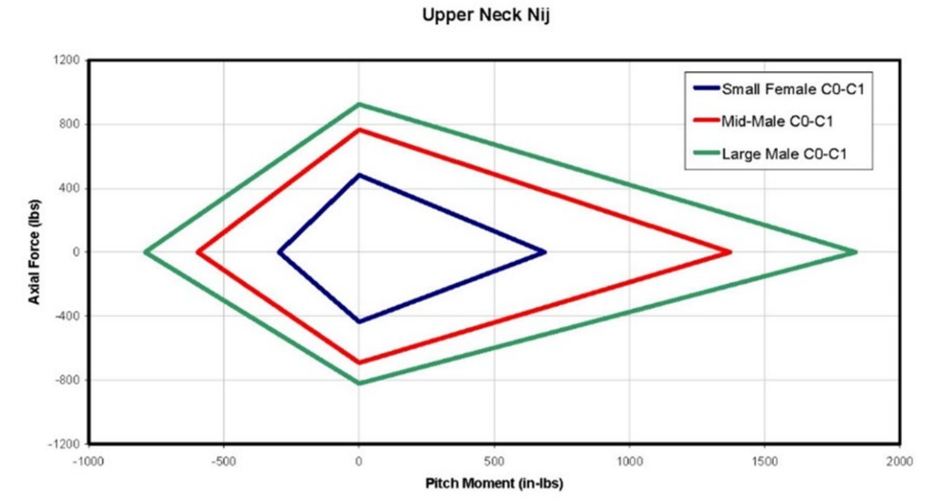


Figure G-5: Upper Neck Nij

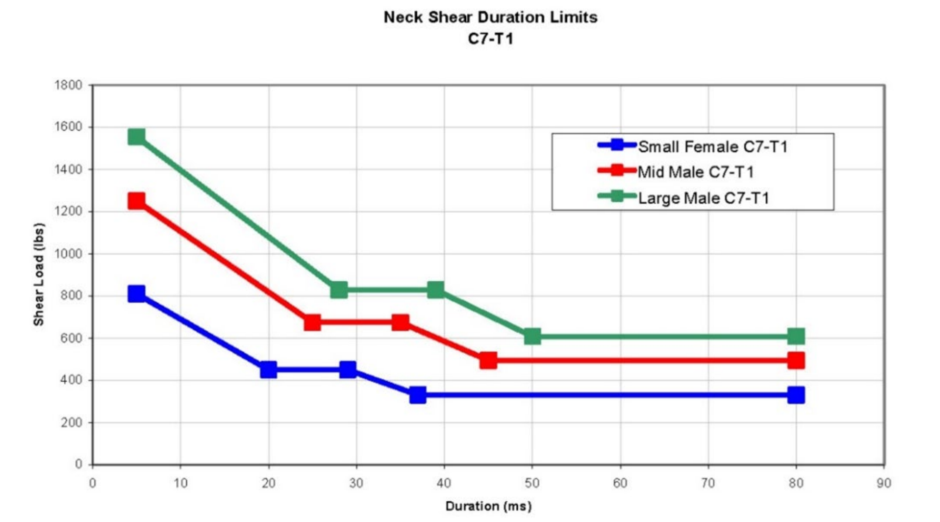


Figure G-4: Neck Shear Duration Limits (C7-T1)

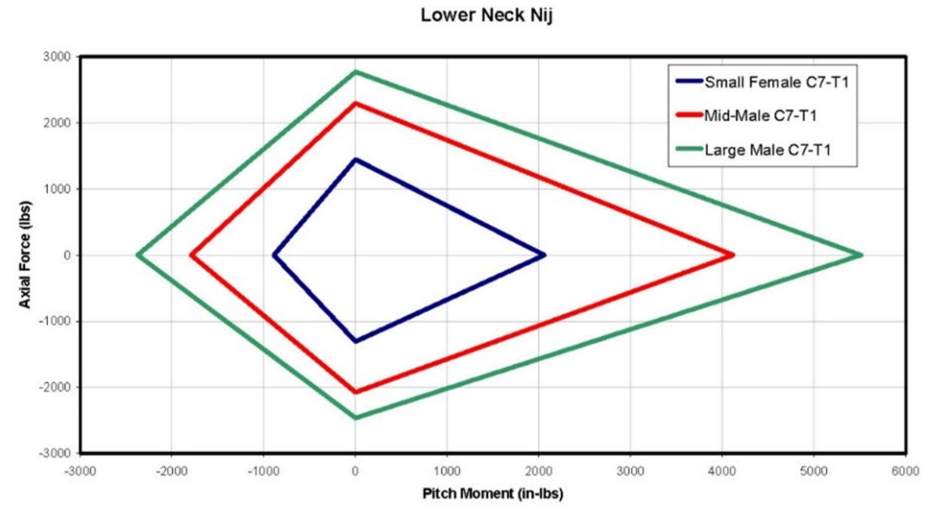


Figure G-6: Lower Neck Nij

MCW Interaction-Based Force and Moment Lower Neck Injury Criteria LNic

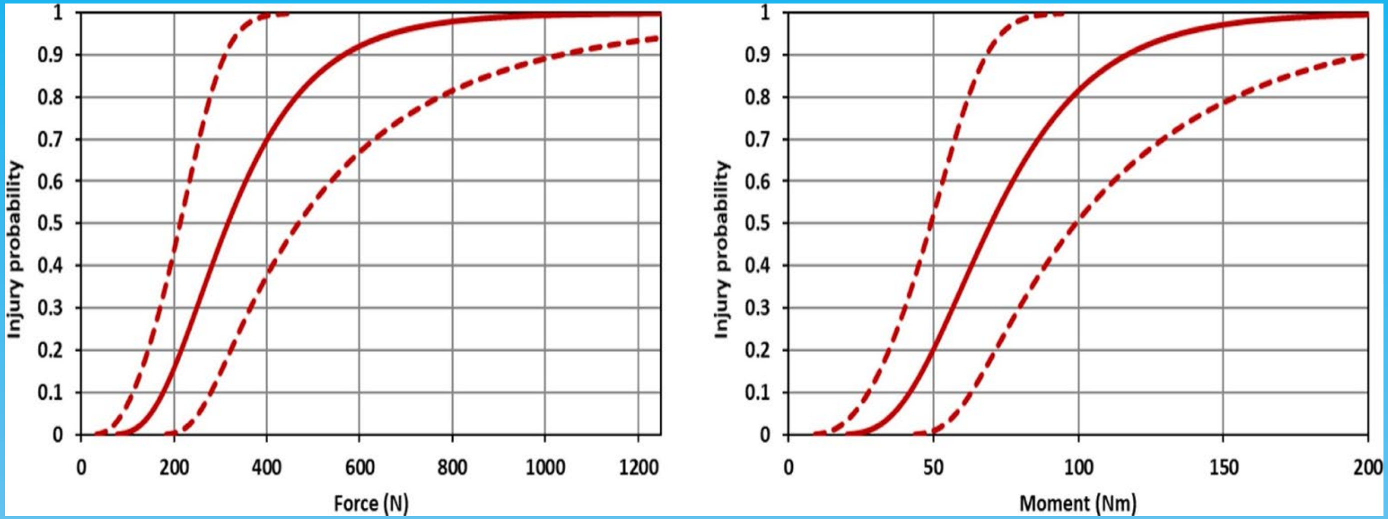
$$LN_{ic}(t) = \frac{F(t)}{F_{crit}} + \frac{M(t)}{M_{crit}}$$

where the time-dependent parameters are:

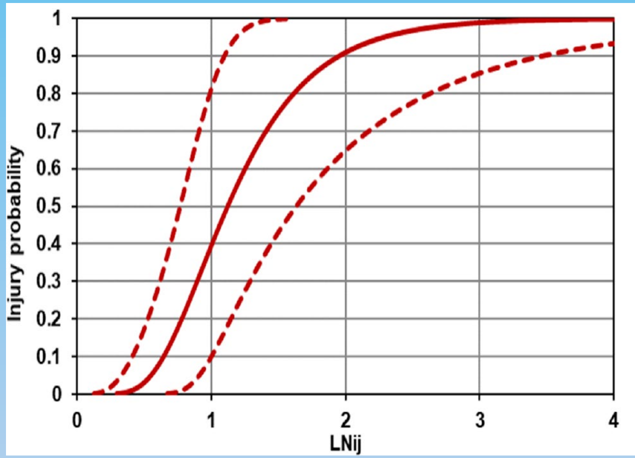
- **F is the A-P shear force**
- **M is the sagittal plane extension bending moment,**
- **subscript "crit" represents the critical intercepts.**

MCW AIS>1 C7-T1 Injury Risk Curves

from Matched-Pair PMHS-H3 Tests under Gx Loading



H3 Force (left) and Moment (right) IARCs



H3 LNij IARCs

For 50% Risk

Mean Force = 315 N

Mean Moment = 70 Nm

MCW Interaction-Based Force and Moment Lower Neck Injury Criteria LNic

$$LN_{ic}(t) = \frac{F(t)}{F_{crit}} + \frac{M(t)}{M_{crit}}$$

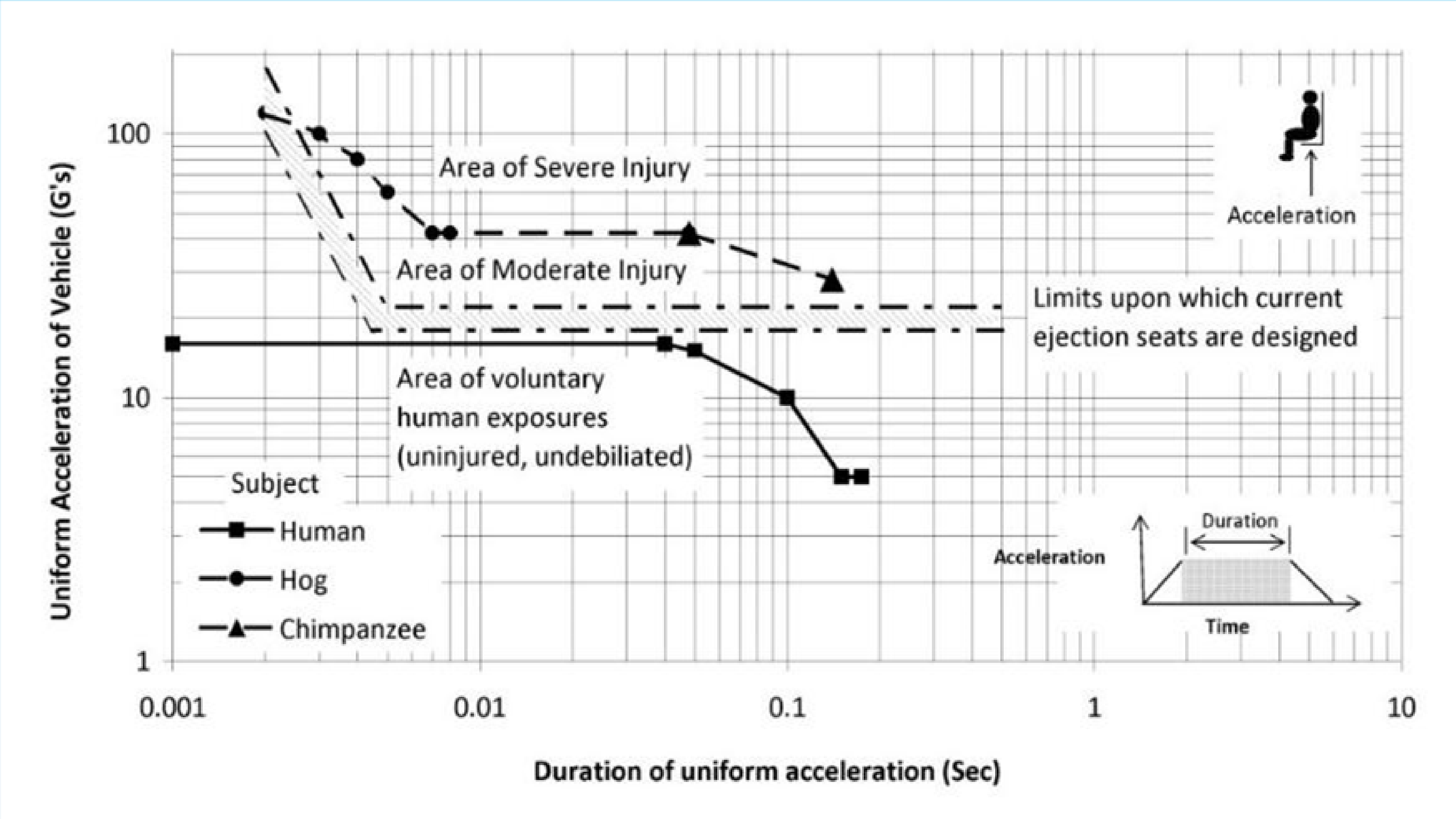
where the time-dependent parameters are:

- **F: A-P shear force**
- **M: sagittal plane extension bending moment,**
- **subscript "crit" represents critical intercepts**

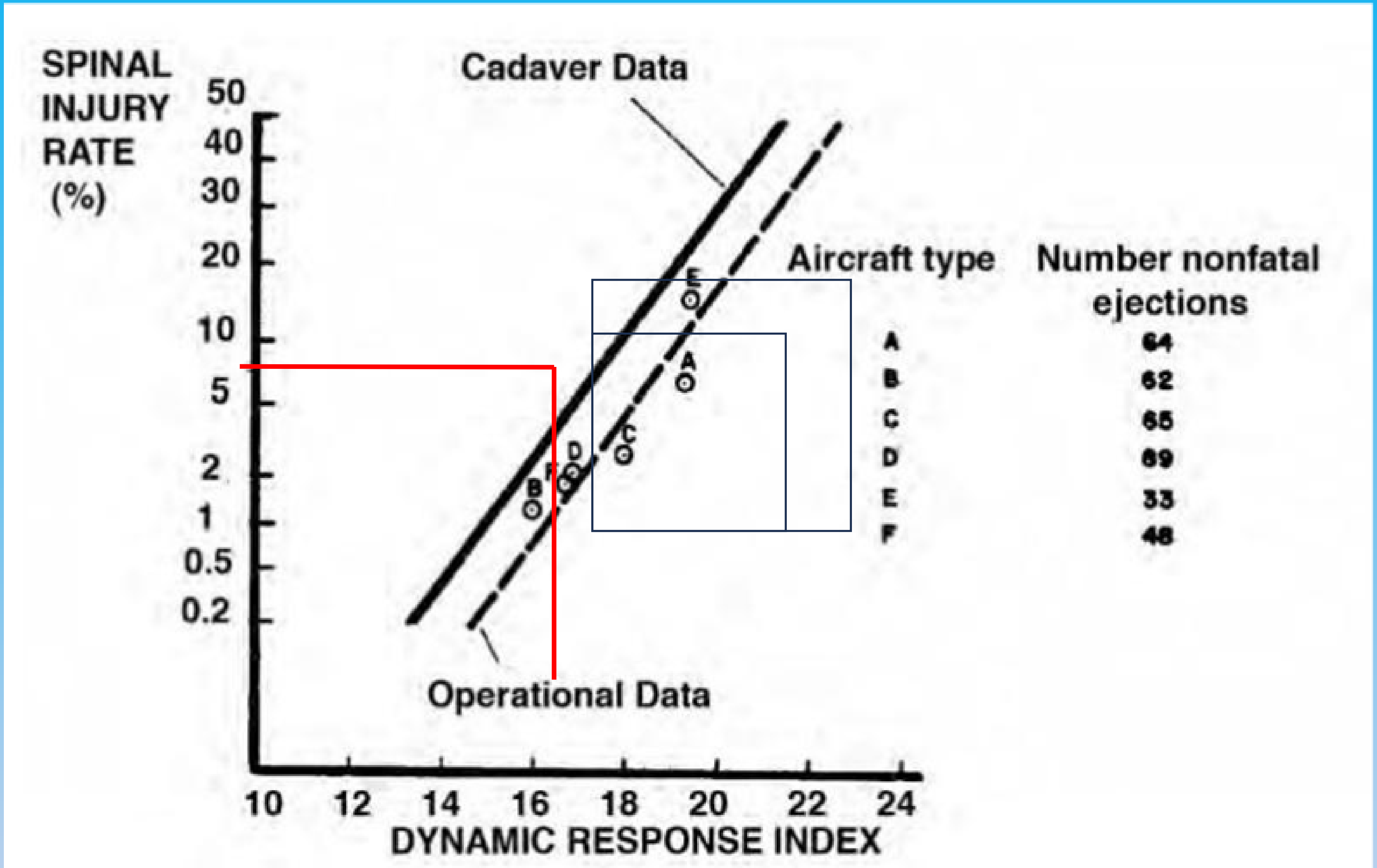
Current Lumbar Injury Criteria for Vertical Loading

	5% Female	5% Male	50% Male	95% Male
Early AF	NA	Eiband	Eiband	Eiband
Army Aviation G vs. ms	≤ 23 ≤ 25	≤ 23 ≤ 25	≤ 23 ≤ 25	≤ 23 ≤ 25
AF, DRI	18 nom	18 nom	18 nom	18 nom
FAA	NA	NA	1500 Lb	NA
JSSG	1281 Lb	NA	2065 Lb	2534 Lb
Army, Ground	G vs. ms, AF DRI, and FAA	G vs. ms, AF DRI, and FAA	G vs. ms, AF DRI, and FAA	G vs. ms, AF DRI, and FAA

Eiband Injury Tolerance Curve for Spineward Acceleration



Dynamic Response Index (DRI)



DRI=18 for 5% Risk of Nonfatal AIS 2+ Spinal Injuries

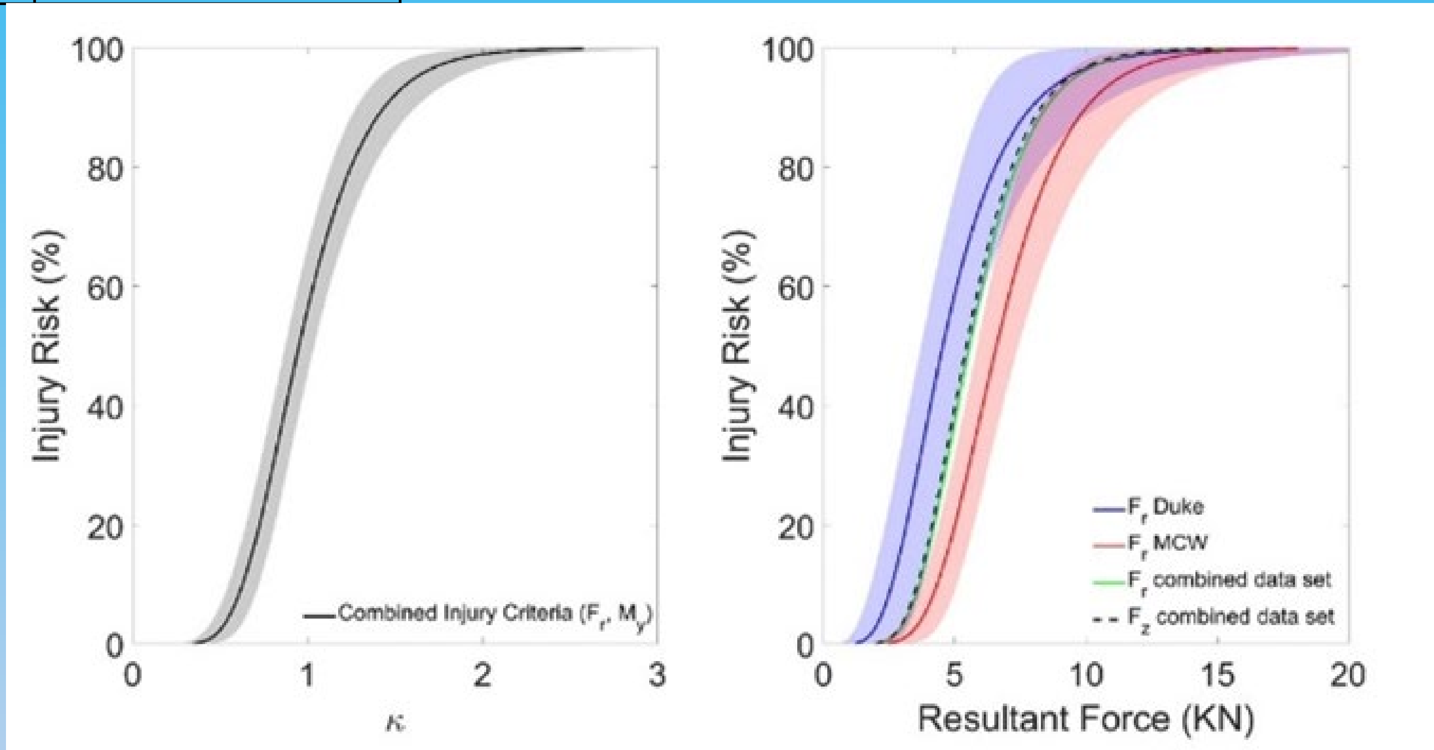
MCW PMHS Lumbar Criteria under Gz Loading

K = Fz/Fz,crit + My/My,crit Risk of T12-L1 Vertebral Body Fracture

optimized for Resultant Sagittal Force Fr,crit=1188# (5824 N) and Bending Moment My,crit= 852 ft# (1155 Nm)

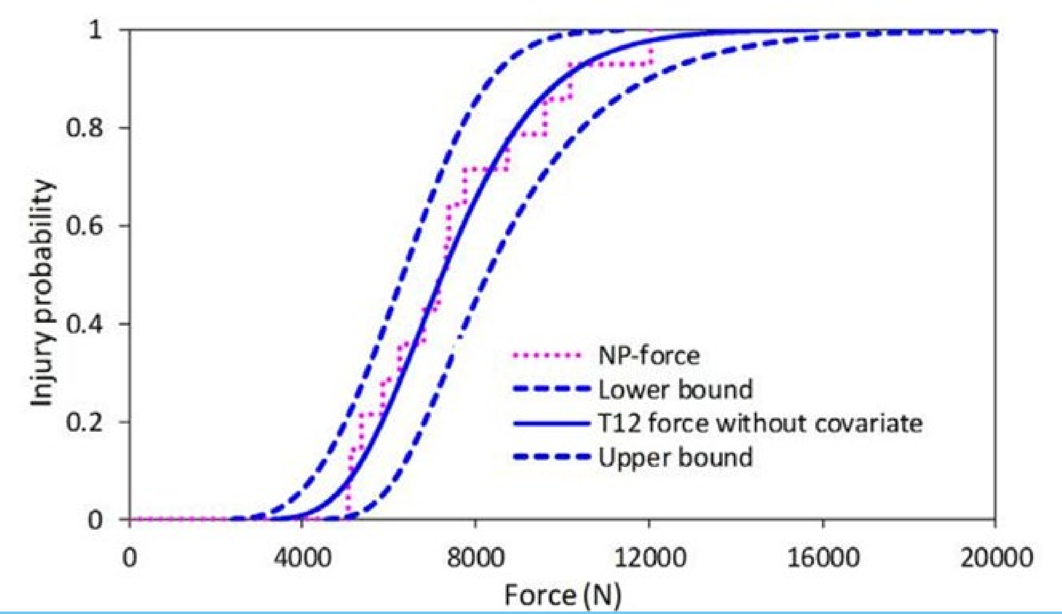
Risk	Combined Metric K
5%	0.59
50%	1
95%	1.70

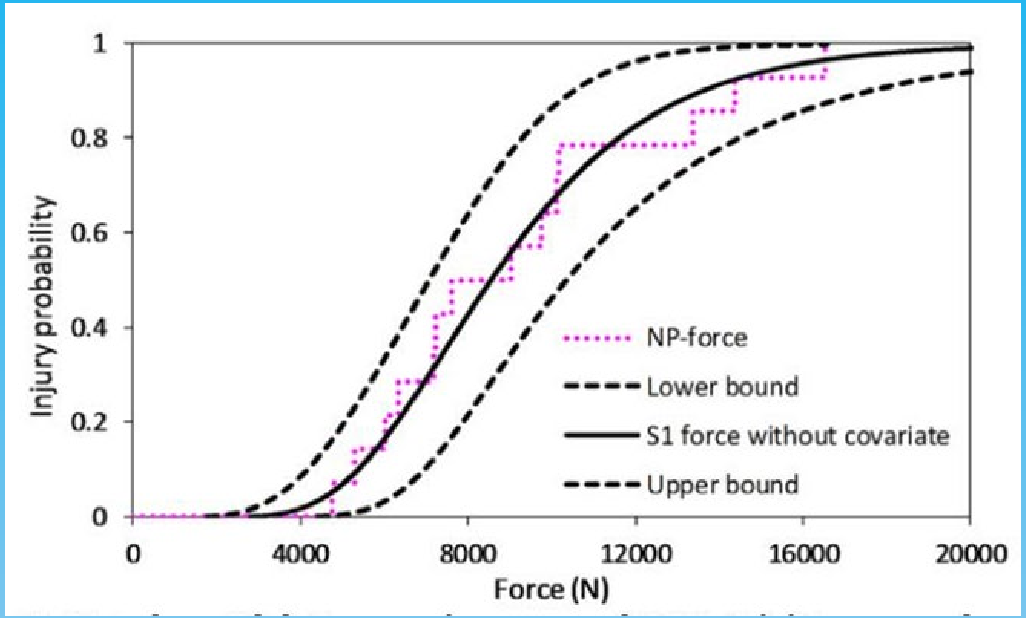
	Resultant Sagittal Force	Risk of Spinal Injury	Combined Metric K
Duke	1021# (4540 N)	50%	1
MSW	1481 (6590 N)	50%	1



MCW PMHS Lumbar Spine Compressive Injury Tolerances

Injury Risk Curves: T12-L1 (Left) and L5-S1 (Right)





Yoganandan et al. 2018	Plot	5% Risk	10% Risk	50% Risk
T12-L1 Force	Left	1068# (4750 N)	1171# (5211 N)	1624# (7223 N)
L5-S1 Force	RIght	1059# (4710 N)	1208# (5372 N)	1921# (8545 N)

THOR-50M ATD Neck

Unlike H3, Lois, Lard, Adam with only 1 load path, the OC pin joint, between the base of the head and the upper neck, the THOR-50M neck has:

- **3 separate load paths, independently instrumented, between base of the head and neck:**
  - **1 OC pin joint, and**
  - **2 cables (1 anterior and 1 posterior).**

Instrumentation:

- **spring load cells which measure the compression at the anterior and posterior spring locations,**
- **6-axis load cells at the top and base of the neck to measure the forces and moments, and**
- **a rotary potentiometer at the OC pin to measure the relative rotation between the head and top of the neck.**

THOR-50M ATD Spine

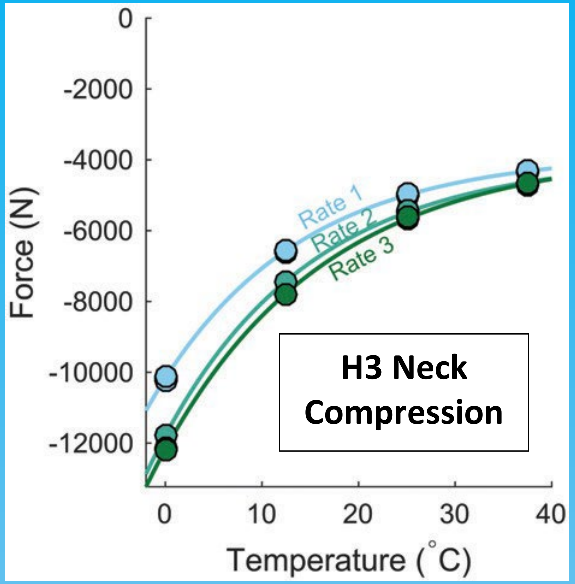
Construction: Primarily steel with

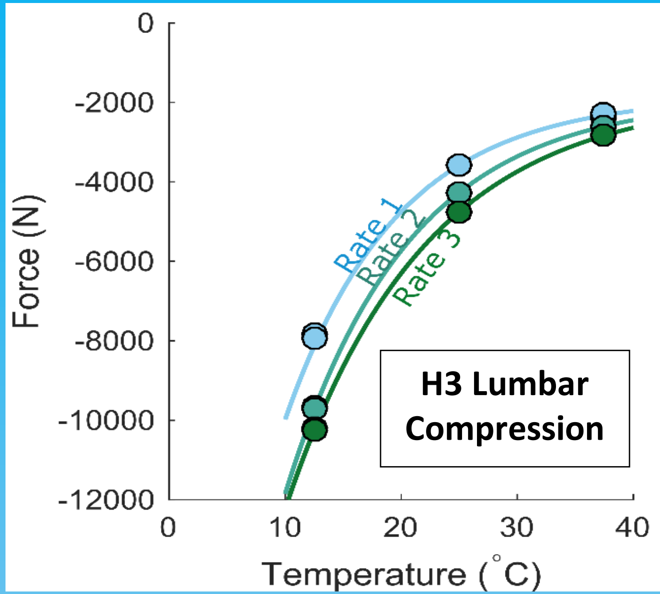
- **a lumbar spine pitch change mechanism, a posture adjustment joint, which allows the posture of the to be adjusted into various seating positions (erect, neutral, slouched, and super slouched) between**
- **2 flexible elements (thoracic spine and lumbar spine)**

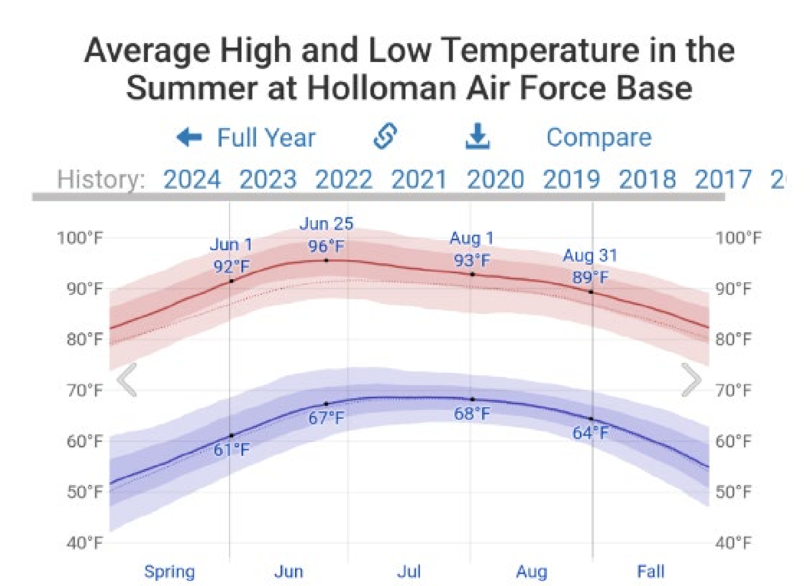
Instrumentation:

- **5-axis thoracic spine load cell mounted below the lumbar spine pitch change mechanism,**
- **5-axis load cell mounted above the lumbar spine flex joint,**
- **Triaxial accelerometers that can be installed in the 1st, 6th and 12th thoracic vertebra.**

Temperature Sensitivity of ATD Neck and Lumbar Spine





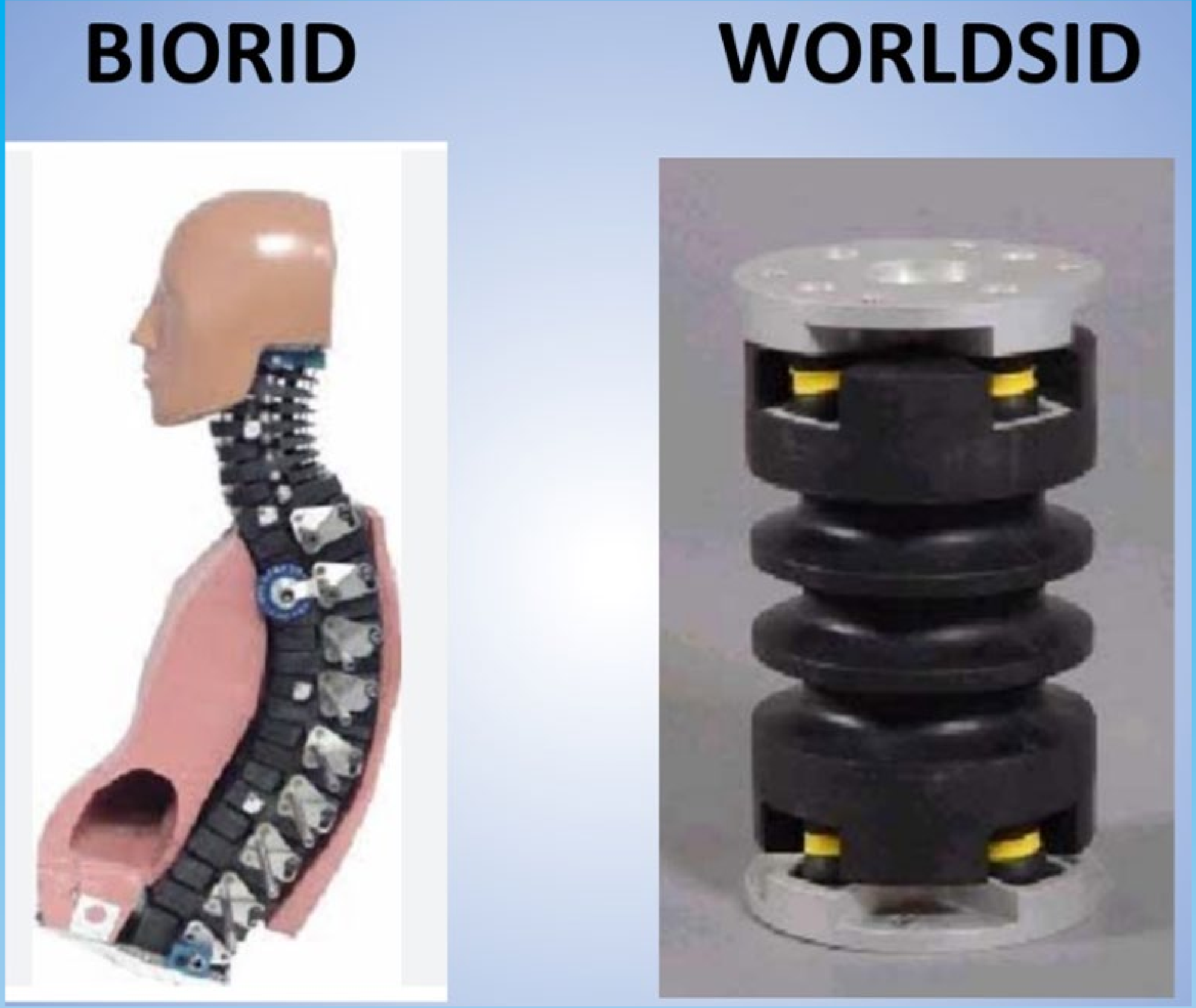


Highest Rate 3 Results

Temp (°C)	Temp (°F)	Neck Force F_{7mm} (N)	Neck Stiffness (N/mm)	Lumbar Force F_{3mm} (N)	Lumbar Stiffness (N/mm)
0	32.2	12173	1739		
12.5	54.6	7784	1112	10216	3405
25	77	5642	806	4754	1584
37.5	99.5	4683	669	2833	944

Temperature had a strong influence on compressive NECK and LUMBAR force and stiffness. Colder temperatures were associated with increased force and stiffness.

- **From 99.5 °F to 32.2 °F, neck compressive force and stiffness doubled.**
- **From 99.5 °F to 54.5 °F, lumbar compressive force and stiffness tripled.**


BIORID
WORLDSID